**KimonoNet  
Enabling Efficient and Reliable Inter-UAV   
Fluid Data Communication Link**

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*KimonoNet addresses a peer-to-peer network research topic related to routing and transport control issues in sparse networks of highly mobile ad hoc peers such as unmanned aerial vehicles. Traditional distance-vector and link-state algorithms are not suited for such a topology given the high mobility and churn of its constituents, which causes routes to shift too quickly for global route propagation. Therefore, this approach leverages a coordinate-based routing system proposed by Greedy Perimeter Stateless Routing and adds two-hop neighbor awareness to minimize control packets and improve reliability in fluid, sparse network graphs.*

# 1. Introduction

## 1.1. Background Information

In recent years, the military has increased computing power in the field significantly; however, the increase in network coverage has not followed suit. One option to increase coverage is deployment of an ad hoc network whereby network-enabled equipment may form routes through a remote operational zone back to a secure base station.

Rather than providing the route via stationary relays, which make for easy targets, unmanned aerial vehicles and other mobile equipment with basic network capabilities may provide such a network in hostile environments. However, a network manifest as a very sparse graph with limited routes to any endpoint. Further, given the mobility of nodes and possible calamities that might befall them, the network may also suffer high churn. Consequently, an implementation must adapt quickly to topological changes and provide reasonable service even when individual route exist only briefly.

Beyond military application, this research topic may provide insight into broader issues in ad hoc networking. To address the dynamics of ad hoc networks, a number of protocols including Ad hoc On-Demand Distance Vector Routing (AODV) and Dynamic Source Routing (DSR) have taken the approach of on-demand routing, ascertaining a path at send-time rather than predetermining routes. However, these protocols suffer from disadvantages including long setup times, inconsistency and unreliability. Other ad hoc protocols such as the Optimized Link State Routing Protocol (OSLR) employ a table-driven approach reminiscent to traditional distance-vector protocols, but they struggle to adequately handle the rapidly changing nature of such a network with inordinate control traffic.

## 1.2. Objectives

Seeking to minimize both setup time and control traffic, this project foregoes traditional distance-vector and link-state protocols, as well as on-demand approaches. Instead, it uses Greedy Perimeter Stateless Routing, a coordinate-based approach first proposed by Karp and Kung [], and then extends it by propagating two-hop neighbor knowledge through control beacons. This strategy increases the interval between beacons, thus reducing control traffic; it also provides the foundation for other improvements based on this knowledge.

To these ends, this project provides a comprehensive description of the KimonoNet protocol including algorithms, message formats, structures, states and functions. While this document summarizes its key principles, a full description of the protocol may be found in *KimonoNet: Protocol Specification Document* [].

Further, this project provides a KimonoNet client prototype that runs under a JVM and provides both a production mode for field deployment and a test mode for simulations.

Finally, this project includes results from simulation that measure the viability and effectiveness of KimonoNet through metrics including packet delivery, routing overhead, average latency and path optimality.

## 1.3. Scope

### 1.3.1. Network Layers

The KimonoNet protocol is an ad hoc mesh overlay. Optimally, this protocol should be implemented directly over Layer 2. However, its flexibility also supports implementations on Layers 3 and 4 that leverage wireless broadcast or multicast.

For convenience, the KimonoNet prototype it built on UDP multicast. To support test mode, it also includes special provisions to simulate multiple nodes in a single environment.

### 1.3.2. Destination Locations

The KimonoNet protocol as described forthwith and in associated material supports mobile source nodes but requires a destination node of known location. In the event that a destination is not static, it assumes that another mechanism will be used to locate the destination. This design decision may present challenges for some communication, but it is purposeful in that it decouples the protocol from search mechanisms, for which significant research has already been devoted.

For simplicity, the prototype client does not provide a search algorithm to locate a mobile destination but instead assumes that the destination is fixed. A flooding search algorithm could be implemented in a future iteration so that a source can locate a mobile destination.

### 1.3.3. Data Payloads

This protocol provides an overlay for routing and transport across a fluid mesh network. As such, the protocol is ambivalent to the data it carries. It relies on the source to package this data and the destination to interpret this data. Consequently, it may transport application-layer data or lower-layer payloads tunneling across KimonoNet.

However, while KimonoNet supports tunneling, the implications of such are not considered forthwith. Users seeking to leverage duplex protocols such as TCP may encounter significant challenges. This is because KimonoNet assumes destinations of known location, and thus requires either a searching algorithm or that the mobile host initiate the communication. However, even when one of these conditions is met, by the time the data propagates to the other party, it may be stale and inaccurate. Large network diameters accentuate this problem.

### 1.3.4. Simplifying Assumptions

This protocol makes two additional simplifying assumptions: (1) it does not consider altitude, and (2) it assumes symmetric communication between any two nodes in the graph whereby, if one node can communicate with another, the reverse is true as well.

## 1.4. Use Cases

Military operations with highly fluid network topologies serve as the motivation for this project. In such scenarios, UAVs and other network-enabled devices move rapidly and may even disappear from the network due to failure or destruction. Consequently, the approach proposed must not require the continuing existence of any node in the network, but it may predict topology changes when possible to help reduce control traffic.

Further, due to the sparse nature of the network graph, the protocol must operate efficiently given limited routing options. The majority of nodes in the network will likely be out of range of any individual node, and thus it must leverage local knowledge and still make near-optimal forwarding decisions.

This routing protocol may extend beyond military operations. It has applicability in any network with high churn where the location and velocity of nodes are generally known. As such, this ad hoc communication protocol could easily support orbiting satellites and maritime expeditions. However, this algorithm will not cover scenarios where location is not available or where velocity changes unexpectedly; in such situations, other approaches are better suited.

## 1.5. Use Cases

Two primary constituents exist in this scenario:

1. Autonomous nodes that send new packets and route received packets.
2. End points that receive data packets routed across the network.

In the motivating scenario, unmanned aerial vehicles meet the former whereas command posts and external uplinks satisfy the latter.

This protocol assumes the initial communication is sent from an autonomous node to an end point of known location. This avoids the need to introduce a search algorithm. However, a full implementation may add such a mechanism to support communication between any pair of nodes in the network and to efficiently support duplex transport.

### 1.5.1. Autonomous Nodes

The primary constituents of the network, autonomous nodes have (1) awareness of their position and velocity, (2) a NIC that supports ad hoc communication, (3) a network layer that supports broadcast, multicast or promiscuous packet delivery, and (4) a running instance of the KimonoNet client. These nodes are regarded as autonomous because they make independent decisions about position and velocity without considering its implications on routing.

Autonomous nodes collect data, accomplish objectives and then seek further instructions. In order to transmit this data or receive further instructions, these nodes introduce data packets into the ad hoc network. These packets are addressed to the known location of an endpoint, and then forwarded through the network based on the routing algorithm.

Beyond introducing packets into the network, autonomous nodes must also receive data packets passed to them by other nodes and then forward them on based on the routing algorithm.

### 1.5.2. End Points

A command post or other external uplink to the Internet serves as the destination endpoint of a packet originating within the ad hoc network. Because this protocol does not consider a mechanism to determine endpoint location, it requires the originator to know the location of the end point and that this position does not change over time.

As with autonomous nodes, end points must also have (1) awareness of their position and velocity, (2) a NIC that supports ad hoc communication, (3) a network layer that supports broadcast, multicast or promiscuous packet delivery, and (4) a running instance of the KimonoNet client.

After receiving a packet from an autonomous node, an end point may use location and velocity information contained within the packet to reply. Because an autonomous node has variable position, all responses from an end point should have QoS classification of time-sensitive and be loss tolerant.

## 1.6. Constraints

### 1.6.1. High Churn

Due to the operating environment, the routing protocol must handle high churn effectively.

Each autonomous node has a velocity that affects its position over time; consequently, the neighborhood for a given node may change swiftly as nodes enter and recede from a network horizon. The routing algorithm handles this by considering two-hop neighbors and extrapolating position over time based on velocity to determine which nodes will be leaving range and which will be entering, thus reducing route maintenance traffic.

Further, given the motivating scenario, nodes may become unavailable unexpectedly due to failure or destruction. The algorithm presented must handle this independent influence on churn adequately, compensating for the fact that a route may become unavailable quickly and without warning. However, this protocol acknowledges that the unexpected disappearance of a node may cause the loss of a packet, but it should take strides to minimize the likelihood.

### 1.6.2. Mixed Horizons

In a sparse network, only a small set of nodes is within range of any individual node; further, adjacent neighborhoods likely share only a few nodes, if any. The routing algorithm must thus take this into account, as adjacent neighborhoods may not be able to communicate directly and a route must instead be established through other nodes to traverse the void.

This constraint is the reason that distance-vector and link-state management is non-optimal: by the time route information has propagated, routes may have changed substantially. This protocol thus operates under the assumption that nodes cannot self-route data through the entire network, and instead that nodes make decisions based solely on their local neighborhood.

## 1.7. Related Work

G. G. Finn proposed greedy route selection for coordinate-based routing in 1987, using a flood-based approach to resolve situations where greedy selection failed []. B. Karp and H. T. Kung reduced routing overhead by providing a method for detouring without flooding by way of graph planarization []. Their work, namely Greedy Perimeter Stateless Routing, serves as the basis for KimonoNet, which is then extended through two-hop awareness for velocity-based prediction of neighborhood changes.

# 2. PROTOCOL

At its heart, the KimonoNet protocol has two primary objectives:

* Nodes provide information that allows other nodes to recognize them as neighbors and predict how their position will change over time.
* Nodes forward data packets through the network to the intended final destination while making near optimal routing decisions at each hop based solely on local network knowledge.

In order to accomplish these goals, KimonoNet leverages work by Karp and Kung on GPSR and extends it such that a node updates its neighborhood proactively based on position and velocity information rather than only when it receives new updates from neighbors.

## 2.1. Beaconing

### 2.1. Beacon Initialization

When a peer first enters the network, it transmits a beacon packet. This beacon packet includes a unique identifier for the node, as well as a location, velocity and timestamp. All nodes within the node’s network horizon receive this beacon and update their routing tables accordingly.

### 2.2. Beacon Updates

At regular intervals, each node transmits a beacon packet similar to the beacon transmitted during initialization. Again, this packet includes a unique identifier for the node, as well as a position, velocity and timestamp. Beyond this information, the beacon includes information about any neighbors that the sender has identified within its network horizon.

Because these beacon packets contain information about both the node and its neighbors, a recipient can build two-hop awareness of both its neighbors and the neighbors of its neighbors, which it may then use to make routing decisions proactively even before it receives updates from these nodes.

### 2.3. Beacon Acknowledgement

When a node receives a beacon that does not include information about itself, it adds the information from the beacon to its own routing table and then responds with a beacon acknowledgement. This response, like recurring beacon updates, should include both the node’s information and information about all nodes within the node’s network horizon.

Beacon acknowledgements exist to reduce the amount of time it takes for a node to learn about its local topology. They provide a form of on-demand awareness whereby, if one node learns about a new node, then this node informs the new node of its existance as well. This procedure will not loop because, once a node learns of another node, it places it in its beacon, and therefore the node will not reply back with its own location again.

## 2.2. Routing

### 2.2.1. Greedy Forwarding

First proposed by G. G. Finn [], greedy forwarding selects the node closest to its final destination. In most topologies, this results in optimal routes because it stays ahead of other possible selections. KimonoNet implements greedy forwarding as its preferred routing mechanism.

When a node running KimonoNet receives a KimonoNet packet in greedy forwarding mode, it determines the closest peer among its neighbors to the destination as follows:

The KimonoNet protocol recommends the haversine formula for the method [*sinnott*]:

When node hardware cannot perform these computations effectively or where network horizons are mathematically insignificant in relation to the Earth’s radius , distances may be computed as if on two-dimensional plane. If ranges are large and precision is not needed to the meter, then the law of cosines provides an alternative. Meanwhile, if ranges are large and the hardware allows, distance calculations might be extended to support the ellipsoid nature of the Earth as opposed to a uniform radius sphere.

The key advantage of greedy routing is that it requires only local knowledge for forwarding decisions. Each router must maintain state only for its immediate neighbors, and beacon packets travel only to immediate neighbors, thus drastically minimizing state and control traffic. This makes greedy forwarding well suited for large, fluid networks because changes do not have to propagate through the whole network, and nodes do not have to keep track of the whole graph, nor any scale-dependent subgraph.

While greedy forwarding makes near optimal path selections under most scenarios, and it requires routers to maintain minimal state, it has two problems that must be acknowledged:

(1) In specially constructed topologies, it can be demonstrated that greedy selection is sub-optimal, potentially to a significant extreme. However, most real-world networks are not constructed as such, and this paper leaves discussion of this issue to related works.

(2) The current node may be a local maxima, namely closer to the destination than any of its neighbors. In this case, the node cannot select a neighbor further away than itself or else the packet may simply loop back. Retreating from a greedy selection also defeats the stay-ahead argument. Therefore, when such a maxima is encountered, it must provide a mechanism to route around the void.

### 2.2.2. Perimeter Forwarding

When first considering greedy forwarding for coordinate-based routing systems, G. G. Finn resolved the local maxima issue via flooding []. However, flooding creates inefficiencies in terms of network traffic, and minimizing these inefficiencies while flooding requires nodes to maintain state. Consequently, B. Karp and H. T. Kung described a perimeter-based alternative that detours around a void when a node is a local maximum [].

KimonoNet implements the perimeter detour approach presented by B. Karp and H. T. Kung. Under this mechanism, when a node is nearer to the destination than any of its neighbors, it switches to perimeter forwarding mode and selects the neighbor sequentially next counter-clockwise from the bearing to the destination. This process continues until the packet reaches a position closer to the destination than when perimeter forwarding began, at which point greedy forwarding may then resume again. If the node undergoes a cycle before this time, then it has encountered an unreachable destination.

This method ensures that a packet will not travel indefinitely because it will be dropped as soon as it reaches the start of the cycle again. However, in order to ensure that all possible nodes are visited, a cycle must not be reached prematurely. To prevent this, B. Karp and H. T. Kung present two methods: a no-crossing heuristic and graph planarization. The former maps perimeters and removes edges that cross a face it has already identified. While B. Karp and H. T. Kung found this worked in 99.5% of cases [], an edge may be removed that partitions the graph. The latter approach does not have this issue because it determines a planar graph and removes edges not in this graph.

When a node running KimonoNet receives a KimonoNet packet in perimeter forwarding mode, it determines the closest peer among its neighbors to the destination as follows:

The KimonoNet protocol recommends the following for the method [*williams*]:

As with , if node hardware cannot perform these computations or network horizons are mathematically insignificant, distances may be computed as if on a two-dimensional plane.

When a packet is in perimeter mode, the state machine for KimonoNet also tries to transition back to greedy mode if possible. Comparing the distance from the destination to both the current node and the node where the packet entered perimeter mode, a transition occurs if the current node is closer. This is because greedy forwarding is near optimal whereas perimeter forwarding is simply meant to detour around a void and get a packet closer to the destination.

The implementation of perimeter forwarding mode stores all necessary state within the packet. This ensures that nodes do not have to increase retained state as the number of packets in perimeter mode increases.

### 2.2.3. Predictive Neighbor Maintenance

Because beacons contain not only location, but also velocity and time, this protocol can perform simple calculations to predict changes to its neighborhood over time even.

In the case of one-hop awareness, this reduces control packets and increases reliability and efficiency. This is because each node knows can compute how its neighbors’ positions will change over time. A node thus knows more quickly when a neighbor is no longer within its network horizon or when a neighbor has moved to a position that makes it more or less optimal for routing, all without the neighbor having to actually send another beacon.

Further, because a beacon includes information not just about a node but also its neighbors, it is thus possible to have two-hop awareness. This both reduces control packets and increases route efficiency. With a simple computation, a node can determine when a neighbor of a neighbor will enter into its network horizon and thus become a direct neighbor itself. This allows a node to more quickly take advantage of another node in its routing decisions, even before the two have explicitly exchanged beacons.

In order to efficiently implement this scheme, KimonoNet uses two routing tables. From received beacons, it maintains a 2-hop routing table of all nodes learned from the beacons. Asynchronous to other tasks, it then uses this two-hop routing table to compute a one-hop routing table of neighbors directly within its network horizon [ § 3.2]. In the beacon packets that the node sends, it includes information about all nodes in its one-hop routing table.

Given the radius of the Earth , the speed of the node , the time since the neighbor information was generated , the bearing of the node , and the location of the node as defined in ROUTING-TABLE-2, the new location may be calculated as [*williams*]:

As with and , alternative, less computationally complex methods may be employed using a two-dimensional plane where necessary and possible. It should be recognized, however, that these calculations are propagated between neighboring nodes through beacons and therefore, while uniformity is not a requisite, a lack thereof may lead to differing ways that nodes regard neighbors.

### 2.2.4. Quality-of-Service

KimonoNet provides three grades of service:

(1) Control data is critical to network integrity such as beacons. It must be transmitted without delay and interpreted immediately upon reception, but it does not require forwarding.

(2) Communication data is time-sensitive data that is forwarded across the network. It is handled in priority over standard data, but in deference to control data.

(3) Standard data is handled when no control or communication data is outstanding to be sent.

The requirements document initially stipulated a fourth QoS garde for reliable data delivery []. However, this version of the protocol does not include support for reliability, as the author quickly found it evident that a good deal more research was needed to effectively implement reliable QoS. More discussion on reliable QoS may be found in § 5.2.3.

# 3. Implementation

**ZORAYR TODO**

# 4. Simulation

**ERIC TODO**

# 5. ConclusionS

## 5.1. Outcomes

**ERIC TODO**

## 5.2. Future Work

### 5.2.1. Modeling and Simulations

The prototype provided some insight into the behavior of KimonoNet. However, it did not conclusively determine whether or not predictive neighbor maintenance based on two-hop awareness fundamentally improves GPSR performance. This is because (1) the graphical simulator was useful for constructing particular routing scenarios, not modeling truely random topologies, and (2) the KiNCoL testing client results did not provide conclusive results but instead suggested that better node behavioral models are needed.

However, while the prototype and its associated simulation environment did not arrive at a distinct conclusion about two-hop awareness, they do provide the framework for future study and research related to KimonoNet via a well-structured object-oriented implementation of the protocol’s structures, algorithms, and functions.

### 5.2.2. Mobile Destination Nodes

As specified in § 1.3.2, neither the protocol nor the implementation provides support for mobile destinations nodes. In the protocol, this is a conscious design decision, as a discovery service is fundamentally different than a routing service, and the protocol seeks to decouple the two so that upgrades to one service do not impact the other. However, any production implementation should provide a discovery service, whereas the prototype in this project does not implement mobile destination discovery, as its primary purpose is to test routing performance.

Support for mobile destination nodes provides two advantages: (1) routing between any two peers in the mesh network and (2) support for duplex protocols. The UAV use case does not require the former use case, but support for duplex communication is needed to implement reliable transport.

### 5.2.3. Reliable Quality-of-Service

Although considered in the project proposal and requirements, a reliable quality-of-service was not implemented as part of this project due to time constraints. However, given an almost-certain need for reliable delivery in military scenarios, KimonoNet should be extended to provide reliable delivery either through tunneling or the network itself.

Tunneling a reliable transport protocol like TCP provides a way to implement reliable delivery. However, as per § 1.3.3, without support for mobile destinations, this is not possible because TCP and other reliable transport protocols requires bi-directional communication so that the destination can acknowledge the reception of stream content. If such duplex communication is implemented within KimonoNet, then this approach benefits from flexibility in that end clients can select a reliable protocol so long as both end points support it. However, it comes at the cost of end-to-end communication to detect and resolve losses, as opposed to network-enforced reliability, which can handled losses locally within transit.

Consequently, the KimonoNet protocol itself could also provide reliable delivery. As opposed to end-to-end reliability, nodes along the transit path may assist with reliability, thus reducing the traffic and time required for loss detection and recovery. However, this requires each node to maintain more state, as well as tightly couples the reliability mechanism into the KimonoNet protocol, making it challenging to make changes later.

### 5.2.4. Predictive Forwarding Delay

The KimonoNet protocol maintains two-hop awareness in order to perform predictive neighbor maintenance. However, it could also more aggressively use this knowledge to delay data forwarding if the topology is anticipated to change favorably. In a relatively fixed network, this doesn’t provide an advantage, because changes will be minimal, but in a highly fluid network, over a relatively short period of time, a neighborhood could change significantly.

As a basic example, consider the case where a node is a local maximum. Under GPSR and the KimonoNet protocol described to this point, the packet would enter perimeter forwarding. However, if a node recognizes that a neighbor in its two-hop routing table will soon become a greedy candidate, it could forestall transmission until that time, and then send the packet via greedy, the preferred routing mechanism. However, the mechanics of this must be explored more thoroughly, as this case will cause selection to fall-behind in time, even if still making an near-optimal route selection.

# 6. Acknowledgements

## 6.1. Group

Given the scope of this project and the limited time constraints, the group divided the work into distinct units of responsibility for each member. In parallel, the team developed the protocol, prototype and simulation environment, and then they integrated these three distinct pieces as the term drew to a close.

Eric Bollens created the conceptual framework for KimonoNet and was the primary author of its documentation. He guided its use of existing protocols and proposed improvements for suited to fluid, sparse networks. He also compiled the project proposal and requirements document and wrote both the protocol specification and the final report.

Zorayr Khalapyan managed architecture of the KimonoNet prototype, including its overall class hierarchy and its implementations of peer packet parceling, beaconing and communication. He also wrote the first draft of the project proposal and assisted with the testing infrastructure.

Wade Norris implemented routing and transport within the KimonoNet prototype based on the protocol specification. This included greedy and perimeter routing and predictive neighbor maintenance. He also contributed heavily to the requirements document.

James Hung developed unit tests for foundation classes in the prototype and then implemented the simulation environment for the KimonoNet prototype. This simulation environment included both the GUI-based simulator and the KiNCoL command-line utility.

## 6.2. Credits

We thank G. Pau, a mentor who advised us throughout this process, which itself was an outcome of his CS 114: Peer-to-Peer Networks class at UCLA.

Further, we thank B. Karp and H. T. Kung for their work on Greedy Perimeter Stateless Routing [], as well as G. G. Finn, who first proposed greedy routing through a coordinate-based system [].

# 7. REFERENCES

**ERIC TODO**

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