Jake Luoma
Network Systems Checkpoint 2
4/16/2020

Summary: I am working on drone swarm communication. The goal of the project is to enable file transfers within and out of a simulated swarm by implementing network functionality from the ground up using OpenFlow and application-level logic. The project steps (numbered below) have not changed. The project proposal has not changed. The implementation details of each section have changed significantly. Each section has been completely rewritten. In each section, I detail what work has been completed or needs to be done along with limitations of the current approach.

1. Set up simulation
2. Implement a neighbor detection algorithm
3. Implement a path selection algorithm
4. Implement data exchange within the swarm
5. Implement data exchange external to the swarm
6. Scalability improvements

Set up Simulation

I have completed simulation setup. See the "Set up Simulation" section from Checkpoint 1 for my discussion about a discussion about what simulation software to use and how to represent the topology. Here, I summarize what I have done. I am using Mininet to drive the simulation and am using Pox as the OpenFlow controller. I have chosen to represent the topology as a set of hosts, each connected to their own switch. The switches are connected with ethernet links with various packet drop rates to simulate transmission propagation and interference. A single controller is connected to all switches and contains the logic for neighbor detection, path selection, and flow rules to support data transfer.

Implement neighbor detection/path selection

I have completed implementation of neighbor detection and path selection. The implementation is different than what I had proposed in Checkpoint 1. They are both performed in a single step, which I think is an improvement over the original ETX paper because it enables better responsiveness to changing network conditions.

When a host spins up, its ARP table is modified so that it knows the IP/mac pair "192.168.1.253 : FF:FF:FF:FF:FF:FD". It sends a UDP message that IP address out the port that is connected to its switch. The switch forwards the packet to the controller, which associates that host with that switch. From here on, all network functionality is implemented by the controller.

Occasionally a timer goes off, prompting the controller to tell each switch to flood its routing table out all ports. Right now, I assume the routing table fits in a single packet. The packet is replicated 5 times to support generation of etx data. The shared information includes tuples of IP, mac, etx, and whether the host has internet access. On receipt of this information, a switch sends the packet to the controller, which tracks the number of packets which actually made it to the switch. Switches do not forward a received routing information packet to other switches. At the end of the time period, the controller calculates etx values, replaces values in the routing table with better entries, and removes entries that are no longer reachable. It does this for each switch. Hosts are notified when the routing table changes, so that they are aware of what other hosts are currently reachable.

On receipt of a packet going from one host to another, the routing table is consulted and, if the path is known, a flow rule is pushed to the switch. If not known, the packet is stored along with an expiry to be forwarded if the destination becomes known.

There are several limitations to the current implementation, listed below. Each is a potential candidate for improvement if I have time.

- Limitation: assuming a single packet can hold entire routing table. Routing tables are limited to <100 entities as a result.
- Limitation: send updates every 3 seconds and batch process. So network changes along a long chain of hosts take 3 seconds * # of hosts in the chain to propagate. I could either increase the refresh rate or change to a streaming approach where etx is calculated with a sliding window. If I were to implement a real system where I know the entire routing table could be sent in a single packet, I would use the streaming approach to ensure rapid propagation of routing information, though the constant updates of routing information might lead to an unstable network. I am not sure how bad of a problem that would be. For this project, I will instead likely mess with the refresh rate to generate some settling time charts.
- Limitation: etx is one-way. Not ideal if using TCP.

Implement data exchange within the swarm

By completing the above sections, I have completed implementation in data exchange within the swarm, at least for direct host to host communication. Retransmission is controlled by the host using TCP. I can send a file directly to another host or I can use ping.

- Limitation: for long chains with lots of losses along the way, use of TCP is very inefficient. It would be more efficient to use UDP and controller logic to implement a pseudo-TCP on each switch along the path (ie. a switch forwards a packet, the next switch receives it, it sends an ack(s) and forwards the packet. The original switch expects an ack and will try forwarding the packet again after a set time if it does not receive one). I'm not going to implement that, but it would be an interesting area for improvement.
- It would be interesting to enable sending a packet which gets propagated to all members of the swarm.

Implement data exchange external to the swarm

This is not implemented yet. I will likely implement intelligence in the controller to recognize when a packet is destined for an IP address exterior to the swarm, use the routing table to identify the closest switch with internet access, and forward the packet towards it. For purposes of my simulation, I will likely simply have the switch with internet access issue a log message saying it received the packet.

Scalability improvements

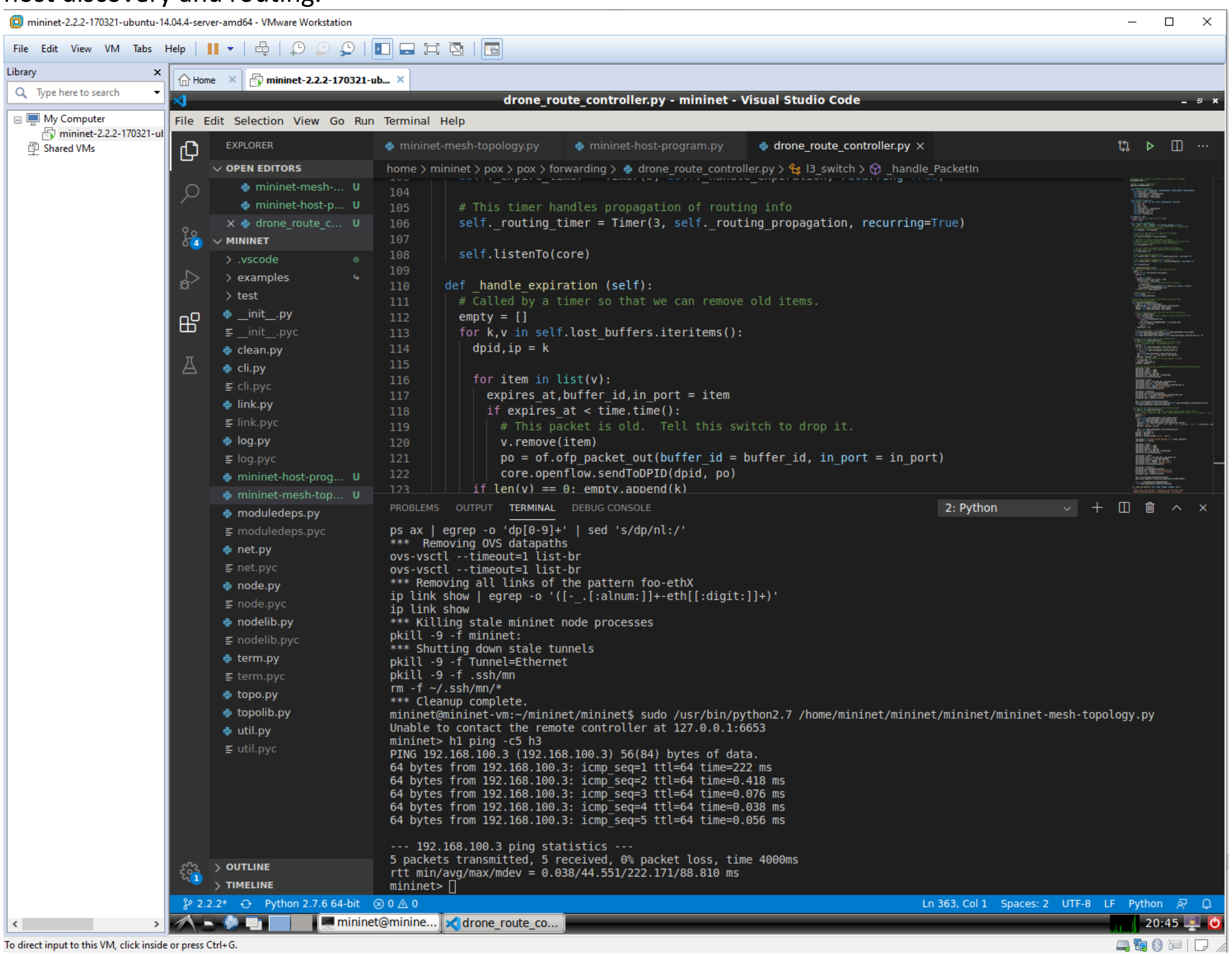
In each section, I have detailed limitations of the current approach. The path selection, congestion awareness, and data exchange can all be significantly improved over what I have suggested. If I get the chance, I might try to implement one of them.

Timeline

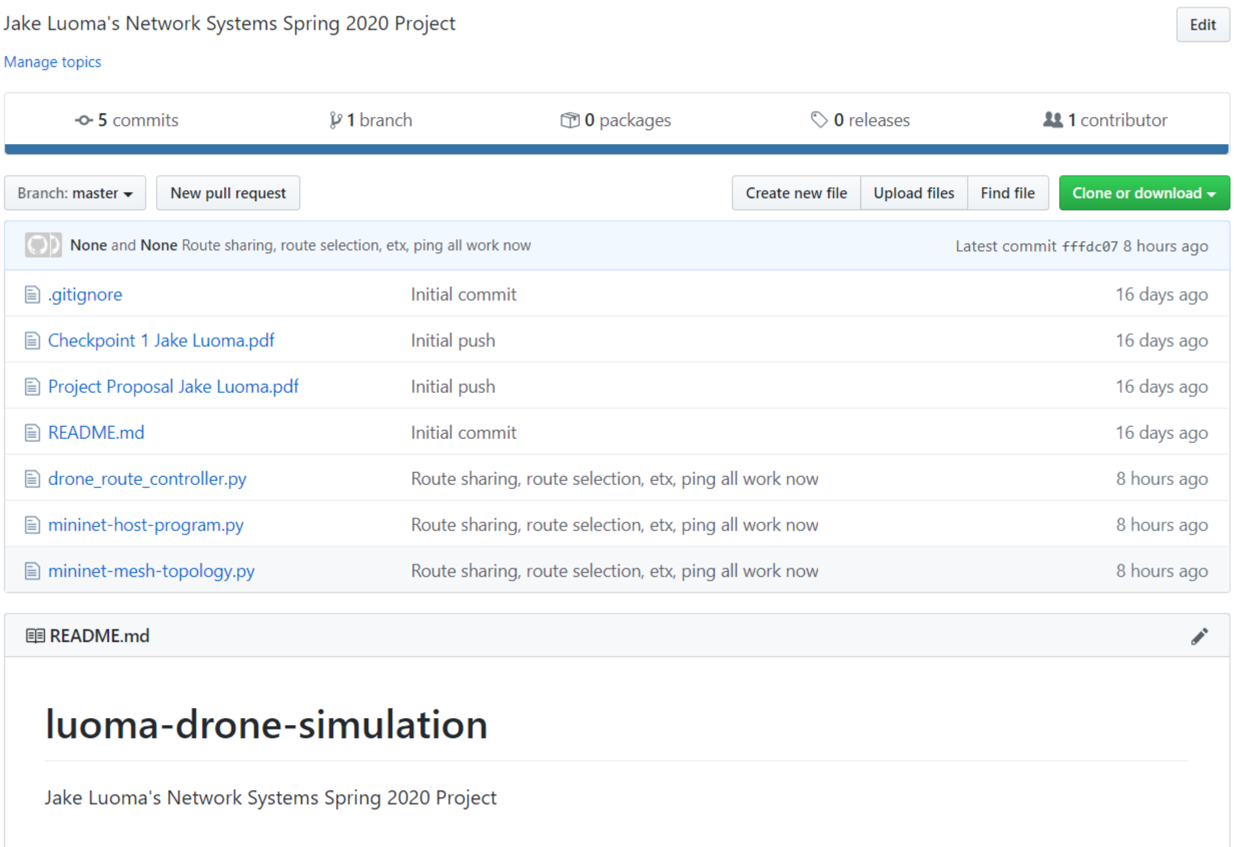
I have completed almost all the basic functionality. During this iteration, I went from a limited simulation environment to most of the implementation work completed. I will finish implementing a mechanism for sending data external to the swarm and then I will switch over to more extensive testing and evaluation. I am on track for completion prior to the project and presentation due date. Scalability improvements are really a stretch goal at this point. At most, I would likely complete one of them. I think there is more value in thinking deeply about their pros/cons and discussing them as part of the presentation to get people thinking critically, so that is where I'm more likely to spend any free time.

Screenshots for check-in

The picture below demonstrates that I can ping between hosts using my custom switch controller for host discovery and routing.



The picture below details the state of the github repo at the time that I wrote this checkpoint.



How the project will be evaluated/validated

There are a few interesting ways this system can be evaluated.

- Characterize how long it takes the system to settle/identify the optimal routes after a major topology change (ie. broken link)
- Characterize how long routing takes to settle depending on refresh rate and topology. The right metric for measuring that might be number of refreshes rather than seconds.
- Characterize how long a file transfer within the swarm takes. Some factors which could be varied include swarm size and packet drop rates.

As far as existing evaluation, I have verified that pinging between two hosts works. As would be expected, the first packet takes orders of magnitude longer than subsequent packets since it has to be sent to the controller for processing.

Challenges

This project has been far more difficult than I expected. Part of it is that I underestimated the work required to model and write custom networking software for a mesh network. Part of it is that Pox's documentation leaves *a lot* to be desired and many of the examples online simply do not work. As a result, getting to this point has been a *massive* struggle. I have learned a ton by implementing everything with OpenFlow/Pox, which is the point of the exercise, but I would probably use P4 instead next time.

Jake Luoma
Network Systems Checkpoint 1
3/31/2020

Summary: I am working on drone swarm communication. The goal of the project is to enable file transfers within and out of a simulated swarm by implementing network functionality from the ground up using OpenFlow and application-level logic. The project steps (numbered below) have not changed. In each section, I detail what work has been completed or needs to be done, along with my thoughts on how I will approach it.

7. Set up simulation
8. Implement a neighbor detection algorithm
9. Implement a path selection algorithm
10. Implement data exchange within the swarm
11. Implement data exchange external to the swarm
12. Scalability improvements

Set up Simulation

I am using Mininet to simulate a wireless network. The OpenFlow controller platform that I'm using is POX. I've installed a VM with Mininet and its associated tools and have written a basic Python script capturing a single network topology and associated controller. There are a couple of advantages and disadvantages to using Mininet.

The advantages are that I can easily define a network topology, change the topology, take advantage of processes running actual TCP/IP stacks, use OpenFlow to program switching behavior and that hosts can run arbitrary applications.

The disadvantages are that I can only run OVS/Openflow on simulated switches (not hosts), POX supports only OpenFlow version 1.0 and therefore has limited programmability, and only ethernet links can be directly simulated.

I think that Mininet will still be adequate for simulation purposes, however. I can specify the behavior of individual links (ie. latency, packet loss rate) to roughly simulate wireless transmission. However, since only switches can run OpenFlow, not hosts, I need to get creative with how the network is represented and how the protocols are coded so that they are functional in the context of the simulation itself. For now, I have connected all hosts to a switch which has OpenFlow rules pushed specifying which hosts a packet from a given host can actually reach. That is done as part of the configuration script. When the time comes, I can simulate network topology changes by changing flow rules. Call this topology 1.

There are a lot of downsides to topology 1. While my code has thus far been written for that, I would like to move over to a topology where every host has its own OpenFlow switch and the switches connect to each other to simulate a connected topology. Call this topology 2. This would allow me to push some of the neighbor detection and routing logic to the switches, rather than the application level as described in later sections. It would also make the simulation more realistic. There's a good chance that I'll switch over to that topology before the next checkpoint.

I considered using Mininet-Wifi instead (it adds wireless links and access points to the base model) and, indeed, I could easily get an adhoc mesh network running with it just using the base simulation software. But modifying routing in adhoc mode with Mininet-Wifi would be very complicated (I believe I'd have to write it in C++ and somehow integrate it in). Instead, I could use a similar topology as above by swapping the switch for an access point. Based on what I've read, it should be straightforward to switch over. However, then all hosts would interfere with each other rather than being grouped properly and only communicating with neighbors. Another alternative would be for each host to be connected to its own AP and do AP to AP communication with mobile APs. The problem is that solution requires hardware support that my laptop doesn't have. So, for the purposes of this project, I think it is more feasible to represent the network using ethernet.

Below, I show implementation plans for topology 1 and topology 2. I will only do one of them, and it will likely be topology 2. The code in the repo is for topology 2.

Implement neighbor detection (topology 1)
I am planning to implement neighbor detection using a combination of OpenFlow rules and application-level logic. The switch needs to statically know the entire network topology at the start of the simulation. For this, it needs rules for dropping host-host packets that aren't allowed by the network topology and it needs rules for replicating host-host packets to all reachable neighbors. Neighbor detection (analogous to ARP requests) will be implemented as an occasional application-level request to a specific IP address/port (irrelevant which, as long as it's consistent). The host application makes a custom raw packet and sends it via the Python socket module. The switch receives the packet, matches on the IP address/port, and forwards to the reachable hosts. These receive the packet and send back a response packet. At the application level, hosts would maintain a map of reachable IP addresses. This packet might be sent out, say 10 times, to deal with packet drops and generate link quality information. To deal with topology changes, if a request goes out to a known host and no response is received for all requests, that host is removed from the list.

Implement neighbor detection (topology 2)
If I swap over to a topology where each host has its own switch, then the rules can be all pushed down to the switches/controllers and they don't need to know the entire topology beforehand. Each switch would only need to be programmed initially with a flow rule specifying that their connected host is on a specific port and to have that information available to share. I will now describe the software running on any given switch. It will have a timer which will go off occasionally. When it does, the switch sends a Hello packet on all ports. All receiving switches respond on all ports with: known MAC addresses of hosts, cost to reach them, and whether they have internet access. When a switch gets this response, it compares its own table of this information with the received information, and changes entries based on cost to reach them and whether a host has become known or out of reach, and updates a first hop field with the MAC address of the switch it received the update from. On any changes to this table, a switch sends the list of reachable IP addresses to its host. Switches track cost metrics to each responding switch by counting the number of sent Hello packets vs received responses – emulating a rough ETX metric. This could be improved through a weighting algorithm which puts more emphasis on recent values, but I'm going to implement it is simple counters to start.

Implement path selection (topology 1)
Path selection will be done primarily at the application level. This is because 1) the proposed simulation topology isn't amenable to doing it at the switch level and 2) data exchange will be done at the application level to ensure data is kept safe if the topology changes and no path to the destination is available.

Network mapping: each host application will have a list of all the other hosts it knows about, a cost to get there based on ETX, the IP address of the first hop to get there, and whether that drone has internet access. Similar to above, a special packet will be sent to all neighbors and a response will be expected. This packet may be sent, say 10x a second, and an ETX value calculated based on the number of received responses. Since links cannot be simulated to have a different drop rate depending on direction, the ETX value will be for a round trip.

Sharing routes: each host application will occasionally share its list of known drones, costs, and first hops with its neighbors. On receipt of a list of known hosts, a host will compare that list to its own. It will add entries that aren't present and it will replace entries for which a lower ETX is available (it adds the ETX to the next hop to the value it received). If a host's list gets updated, it will send its updated list to its neighbors. If a host has a destination with a given first hop, and it receives a list from the first hop that no longer has the destination in it, then it removes the entry from its list.

Implement path selection (topology 2)
If I swap over to the topology where each host has its own switch, path selection is easier because the cost metric and list of reachable hosts/first hops is generated by hello messages. The data is simply forwarded to the next hop. If the recipient is unreachable, the controller will store the packets for a short time before deleting them. If the destination becomes available before then, the packets get forwarded. This can be improved by adding versioning to packets, but I will leave that for future work.

Implement data exchange within the swarm (topology 1)
Drones must be able to store another drone's sent data if the topology changes and a path to the destination drone is no longer available. I propose that a host application on a specific port should be dedicated to data exchange within the swarm so that data can be stored in user space until a path becomes available. A drone would send its data to the next hop's data handling application via FTP, along with the final destination IP address. The data handling application would then attempt to forward the data. In the event of a failure to send due to timeout, the application would occasionally try again to send the data. If the drone is the final destination, it keeps the data. For data that is being held until a path becomes available, a timer should be in place to delete it if it becomes too old. Similarly, sent data should be associated with a version number. If a drone holding data receives a newer version of that data, the old version is replaced.

Implement data exchange within the swarm (topology 2)
Packets sent to an IP address within the swarm are forwarded, stored, or deleted as described in the path selection section. Packets should be sent via TCP so that the application knows to resend the packets if a response is not received. I know that this will decrease performance when the number of hops increases, but I want to start simply.

Implement data exchange external to the swarm (topology 1)
I propose that drones with internet access advertise it as part of path selection. Then, similar to data exchange within the swarm, data will be sent to a specific port via FTP which is responsible for holding onto the data in case of the path to the destination becomes unavailable. The data is sent to the next hop, along with the destination IP address. If the drone has internet access, it sends it to the internet using FTP.

Implement data exchange external to the swarm (topology 2)

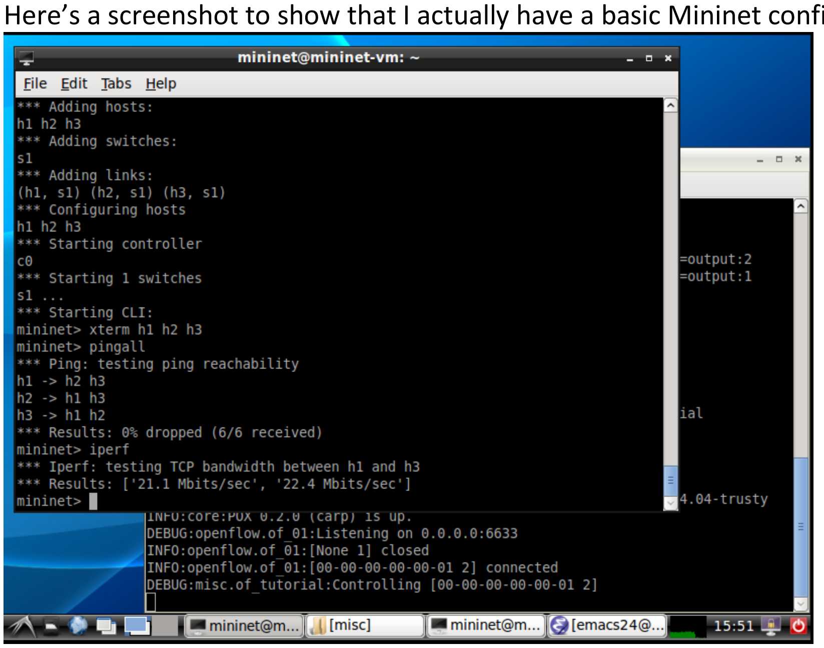
Similar to data exchange within the swarm, but if the packet is destined for port 80, then it is routed to the host with the lowest path cost that has internet access.

Scalability improvements
The path selection, congestion awareness, and data exchange can all be significantly improved over what I've suggested. Once the system is working, I will solicit feedback on what I might focus on. I will also stress test it (ie. change the number of drones in the swarm, change the time between network changes, change the neighbor detection frequency, etc.) to try to identify failure points.

Timeline
I have the basic simulation set up now. Next is swapping over to topology 2 and implementation of neighbor identification and path selection. Data exchange will then be fairly straightforward application-level logic. My goal is to have implementation done by the next checkpoint. Then, I can focus on testing the system, writing the final report, and making some improvements to the system for the final checkpoint.

Screenshots for check-ins
I haven't pushed any code for the check-ins yet but I do have Mininet working and a basic single switch topology communicating properly, along with a nice python configuration script describing the topology and a basic script for the OpenFlow controller. I've spent a lot of my time thinking about the tools available to me, their capabilities/limitations and the architecture required as a result. I think that spending my time thinking about logistics was better than jumping in head-first. I'm going to start (and hopefully finish) coding during this iteration. I want to get most of the code written this weekend. The code pushed as part of this checkpoint is the code that I've written so far in support of the topology 2 rewrite.

Here's a screenshot to show that I actually have a basic Mininet configuration working 😊



How the project will be evaluated/validated
There are a few interesting ways this system can be evaluated. One is to determine how long it takes the system to settle/identify the optimal routes after a major topology change. Another is to determine

how long a file transfer within the swarm takes. Some factors which could be varied include swarm size and packet drop rates.

Jake Luoma
Network Systems Project Proposal
3/5/2020

Summary: I propose to work on drone swarm communication. At a high level, the project can be described with the following series of steps. Each step is described in greater detail below.

13. Set up simulation
14. Implement a neighbor detection algorithm
15. Implement a path selection algorithm
16. Implement data exchange within the swarm
17. Implement data exchange external to the swarm
18. Scalability improvements

Set up Simulation

One aspect of the simulation involves specifying which drones can communicate with each other. This may be specified as a list of drone pairs, where each pair can communicate. It can be modelled in a simulation software as a set of trees of routers and hosts. Alternatively, it could be modelled in Linux such that all drones are modelled as hosts all connected to a router whose forwarding behavior is controlled by iptables.

Another aspect of the simulation is the time element. The network topology should change over time, so a clock is required to determine when the topology changes. The network can transition between multiple topologies simply by using multiple lists of drone pairs and changing from one list to another after a certain amount of time has passed.

Implement neighbor detection

I propose that drones ping hello messages every x seconds with a sequence of Hello, Ack, Ack. Each drone must also be capable of running BGP to identify whether it can connect to the internet. Separate routing tables should be used for destinations within the swarm and destinations exterior to the swarm.

Implement path selection

I'm not sure how I want to do this yet. Congestion-awareness will be very important, but I haven't decided whether I want drones to make locally optimal decisions (ie. a BGP-like protocol with congestion awareness a la DCTCP) or globally optimal decisions (ie. full swarm awareness with congestion awareness based on RTT and/or available bandwidth). I may start with the locally optimal approach. To deal with changing topology, it will be necessary to either store multiple paths to a destination or to run neighbor detection and path selection again when multiple timeouts are encountered.

Implement data exchange within the swarm

Drones must be able to store another drone's sent data if the topology changes and a path to the destination drone is no longer available. I propose that an application should be dedicated to data exchange within the swarm so that data can be stored in user space until a path becomes available. A drone would send its data to the next hop's data handling application via FTP, along with the final destination IP address and socket. The data handling application would then attempt to forward the data. In the event of a failure to send due to timeout, the application would occasionally try again to send the data. If the drone is the final destination, the application will forward the data to the correct socket. The performance can be improved through use of DPDK, XDP, or PF_RING. I propose to initially use the default TCP/IP stack.

Implement data exchange external to the swarm

I propose that drones with internet access advertise it as part of path selection. Then, similar to data exchange within the swarm, data will be sent to a specific application running on each host via FTP which is responsible for holding onto the data in case of the path to the destination becomes unavailable. The data is sent to the next hop, along with the destination IP address and a flag indicating it is external to the swarm. If the drone has internet access, it sends it to the internet using FTP.

Scalability improvements

The path selection, congestion awareness, and data exchange can all be significantly improved over what I've suggested. Once the system is working, I will solicit feedback on what I might focus on. I will also stress test it (ie. change the number of drones in the swarm, change the time between network changes, change the neighbor detection frequency, etc.) to try to identify failure points.