Investigating NDN Forwarding without Routing for Resource-Constrained Wireless Mobile Networks

Lan Wang , Alexander Lane (University of Memphis)
Constantin Serban, Jesse Elwell (Peraton Labs)
Alex Afanasyev (Florida International University)
Lixia Zhang (UCLA)

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  - ASF (Adaptive SRTT-based Forwarding Strategy) Design
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Motivation: Challenges in Wireless Mobile Environments

- Previous studies largely focused on wired networks
- Mobile ad hoc environments
  - Reachable nodes and paths change frequently, making measurements and knowledge of the network quickly become obsolete
  - Higher risk of network partition
  - Resource constraints of low bandwidth (e.g. under 2 Mbit/s) and low-power devices
- Routing is often unviable in ad hoc
- Many NDN forwarding strategies are specifically unsuited for low bandwidth environments

Motivation: Challenges in Running Routing Protocols in Ad Hoc Mobile Environment

- High degree of connectivity dynamics leads to high routing protocol overhead
  - An illustration: a network of 100 links with each link changing every 5min → one link-state update flooding every 3 seconds
  - Slow routing convergence
- Each NDN router keeps forwarding state, which enables adaptive forwarding
- This study: is it possible to solely use forwarding strategies in wireless mobile NDN networks?

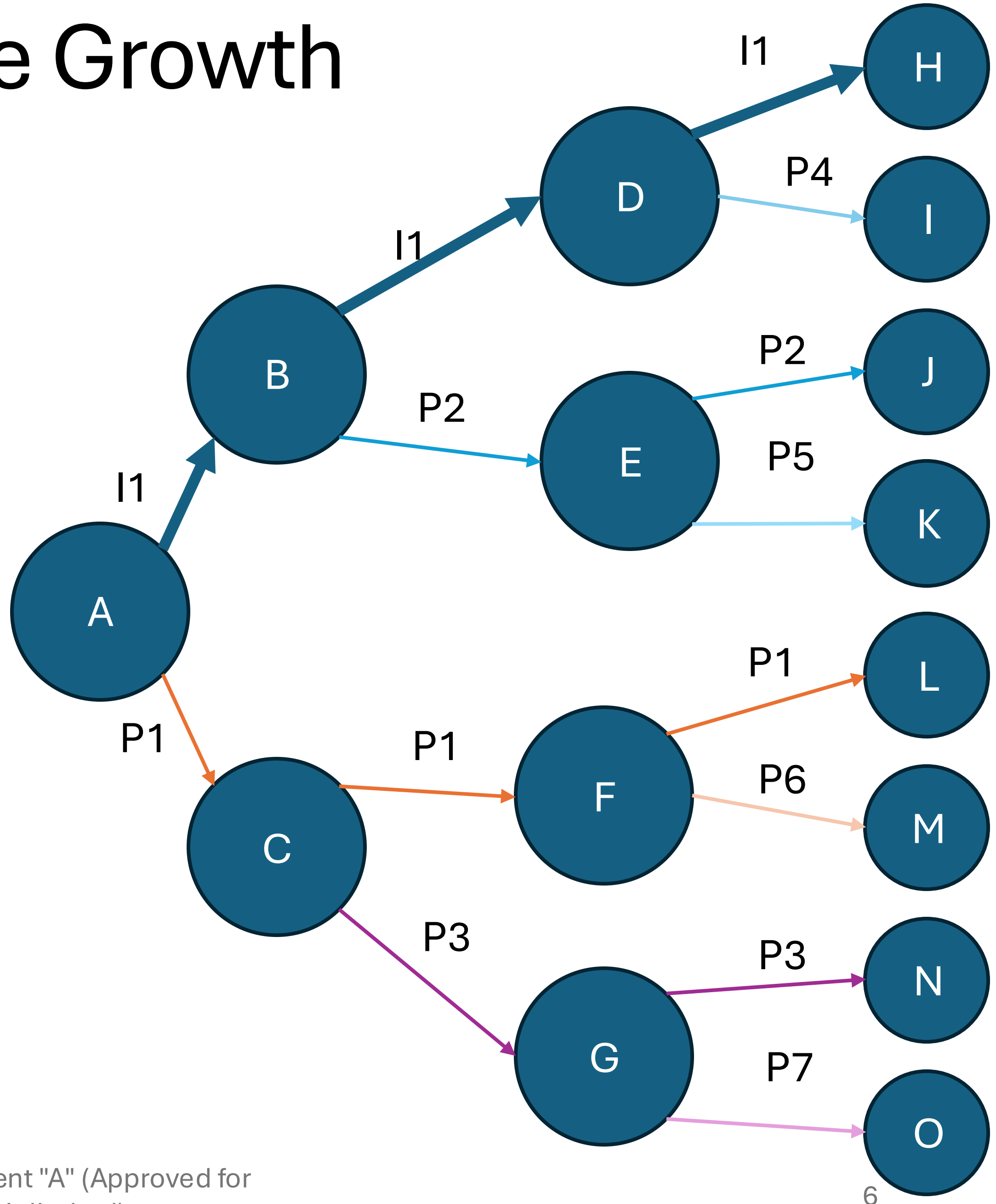
Motivation: High Overhead of Existing NDN Forwarding Strategies

- Experimented with Adaptive SRTT-based Forwarding Strategy (ASF) in a wireless mobile network
- Overhead due to ASF: 95.58%
  - Mostly redundant data returns due to ASF's probing mechanism
- Observed in wired networks [1], but less apparent due to higher bandwidth and lower dynamics in wired networks.

Outgoing Network Traffic	Rate (kbps)	Percentage
ASF Probe Interests	93.58	2.46%
ASF Probe Triggered Redundant Data	3545.53	93.12%
Other Overhead	4.30	0.11%
Application Interests	19.16	0.50%
Application Data	107.43	2.82%
Nacks	37.55	0.99%

Motivation: Exponential Probe Growth

- Probes can trigger other probes if probing is due on multiple nodes on a path.
- Worse case generates $2^{n+1} – (n+2)$ probe Interest packets for the same data, where n is the longest path length.
    - Note: each hop can generate at most one additional probe in ASF.



Goal and Approach

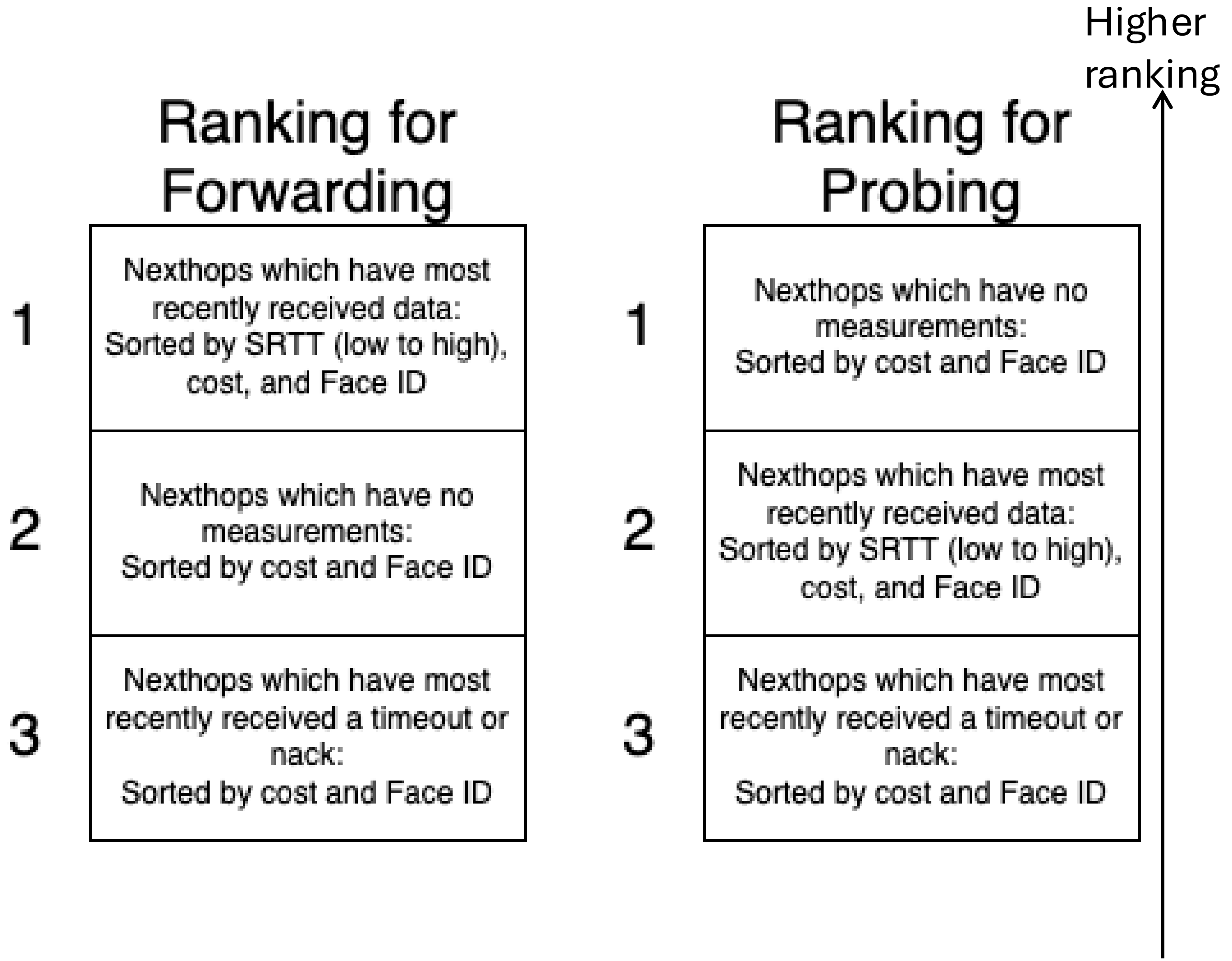
- Goal: achieve near optimal data delivery with low overhead in a resource-constrained wireless mobile environment
- Approach: investigate the feasibility of adaptive NDN forwarding *without* routing in wireless mobile networks
  - Use “Link Manager” to detect and establish connectivity
  - Adapt the ASF strategy to wireless mobile environments
  - Compare data delivery performance with that under optimal forwarding

Background: Link Manager

- Utility to detect and establish connectivity between adjacent nodes
- Assume pre-existing knowledge of name prefixes
- Use multicast beacons to announce liveliness to other nodes within wireless range
- Add or remove nexthops dynamically in the forwarding table based on detected wireless connectivity to nearby nodes

Background: ASF (Adaptive SRTT-Based Forwarding)

- ASF aims to find paths with shortest delay [2]
- Use NDN's Interest-Data exchanges to measure RTTs
- Rank faces based on smoothed RTT (SRTT), timeouts/Nacks, path cost, break ties by face IDs
- When forwarding an Interest, send a copy of the Interest with a different nonce (i.e., probe) to another nexthop to find better paths if probing is due.
  - Use the ranking algorithm for probing to select the nexthop to probe.
  - Probing is due if the time since the last probe has exceeded a configured probing interval.

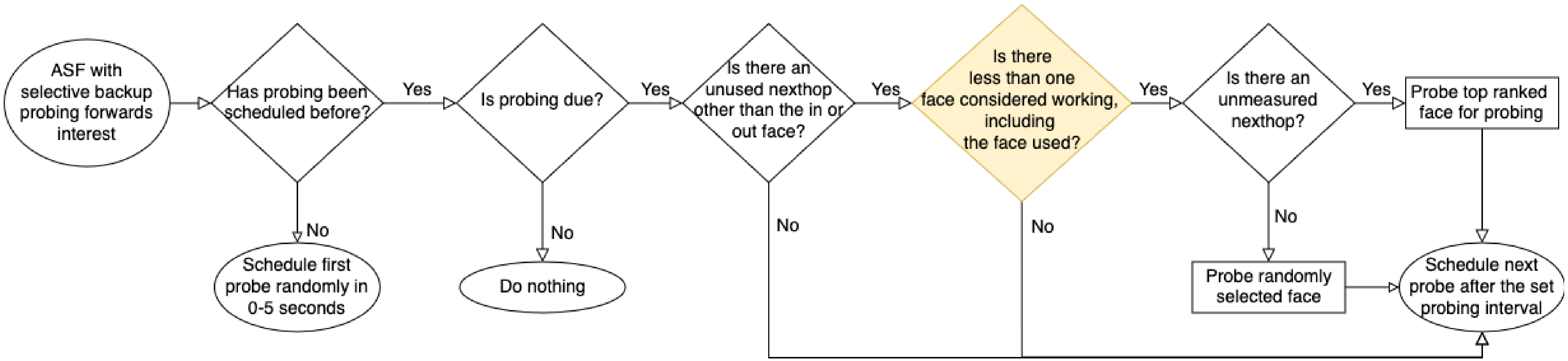


Design: Selective Backup Probing

- Question: If we focus on reachability rather than minimizing delay, can we send fewer ASF probes?
- Approach: Selective Backup Probing
  - Do not probe if there is at least one working nexthop (i.e., a nexthop that has most recently received data)
- Other approaches we tried but did not adopt
  - Having more than one working nexthop produced significantly higher overhead without obvious benefits
  - Purely reactive probing without an interval when no nexthop is working caused too much overhead during network partitions

Design: Selective Backup Probing

only one simple change in the ASF probing function

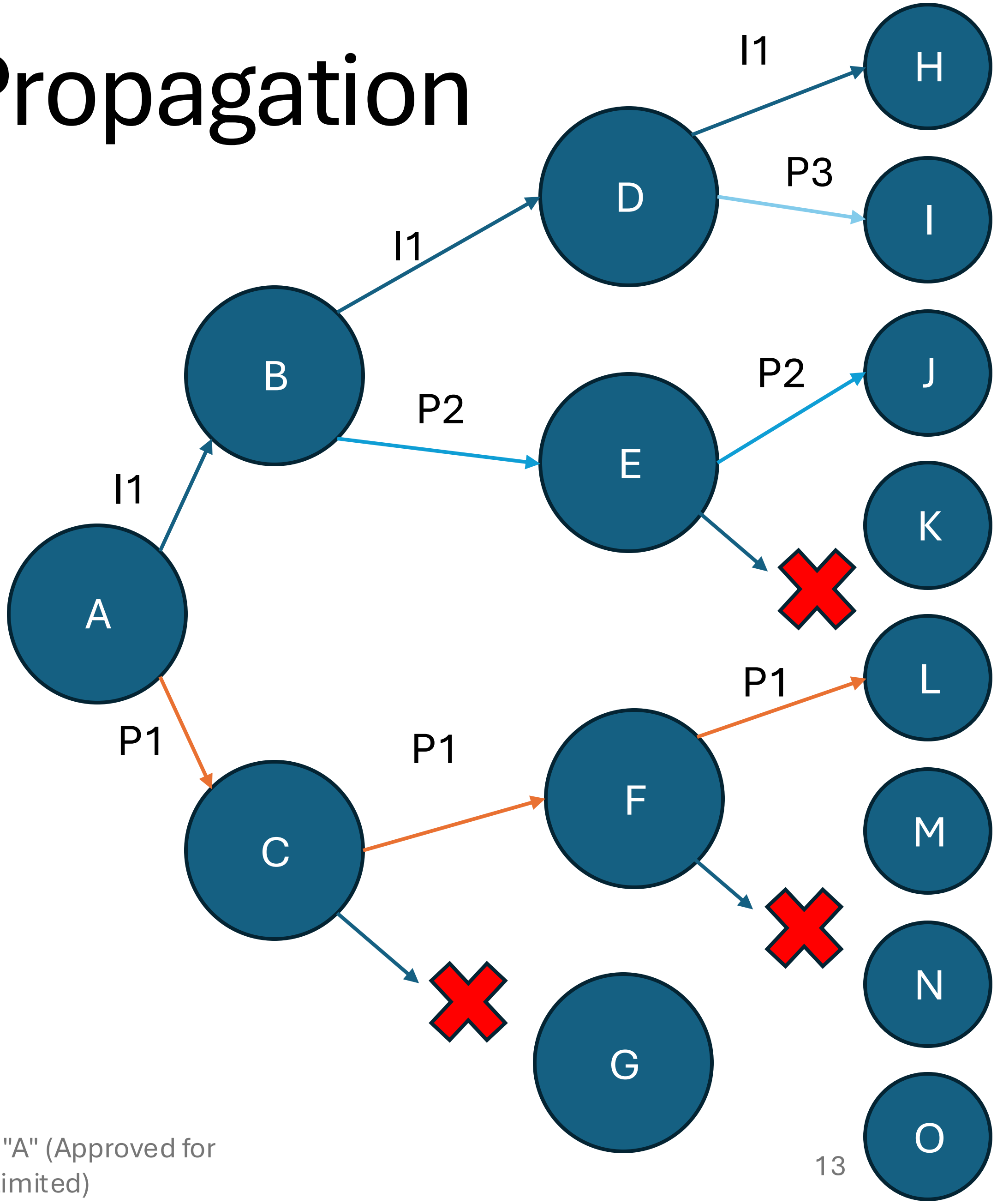


Design: Controlled Probe Propagation

- Problem: We need a mechanism to prevent ASF probes from triggering new probes
- Approach: Controlled Probe Propagation
  - Mark these probes with a specific nonce
  - Forward as normal
  - Do not send a probe if you receive an Interest with this nonce
  - Do not send Nacks for Interests with this nonce

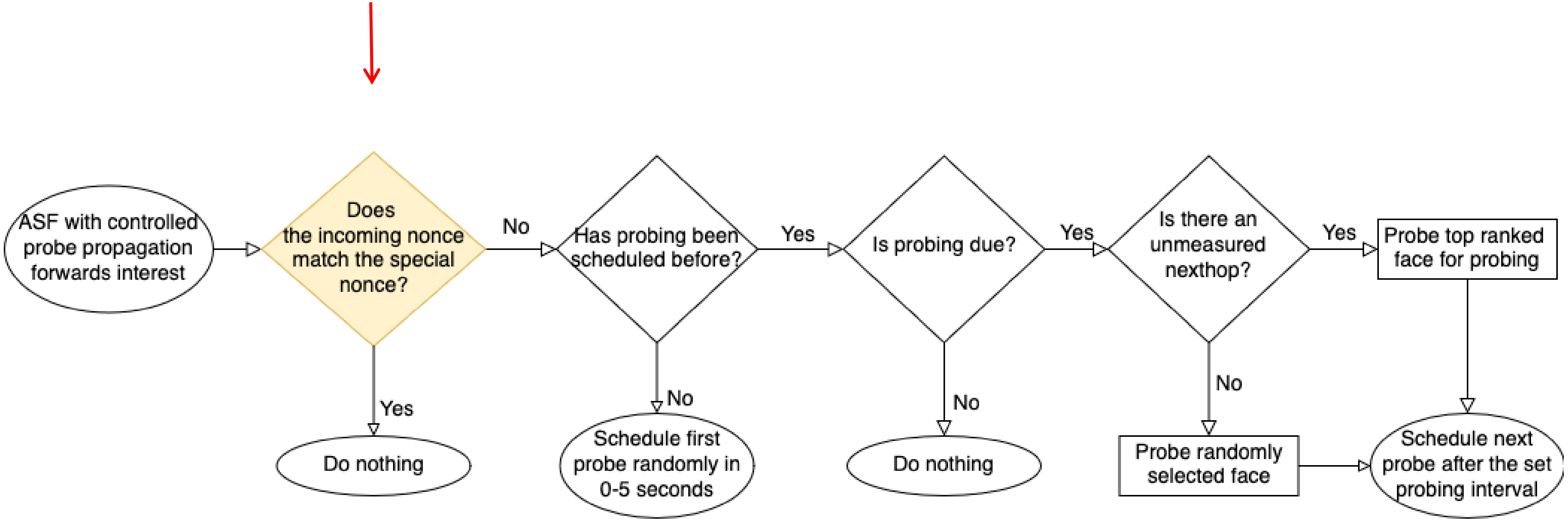
Design: Controlled Probe Propagation

- Since probes will not trigger other probes, worse case is n(n+1)/2 probe Interest packets for the same data where n is the longest path length.
  - Note: each hop can generate at most one additional probe in ASF.



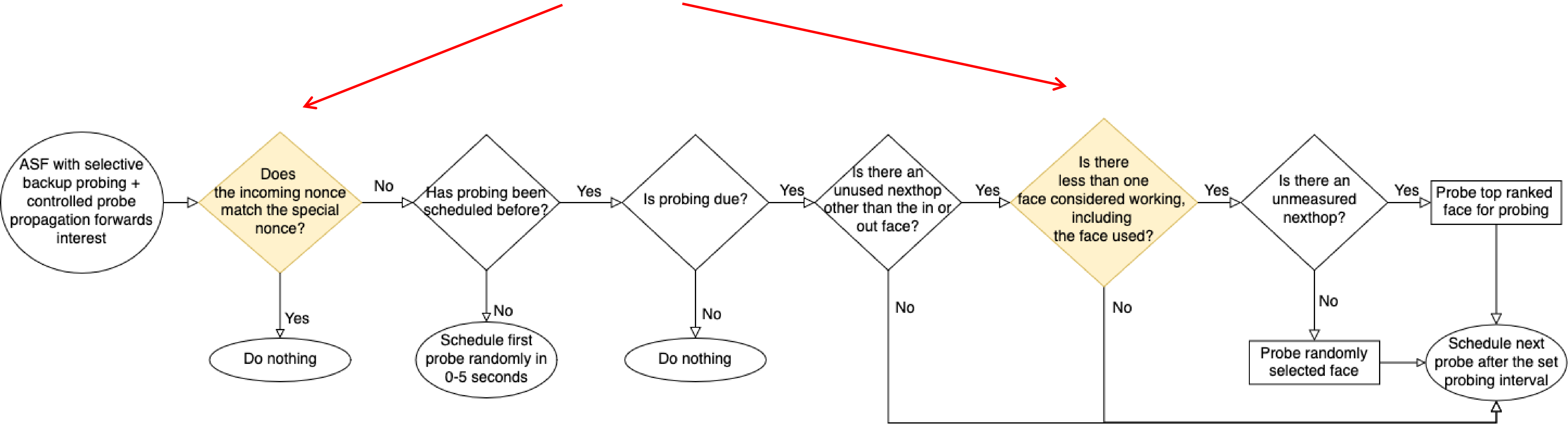
Design: Controlled Probe Propagation

only one simple change to the ASF probing function



Design: Combination

only two simple changes to the ASF probing function



Evaluation: Experiment Design

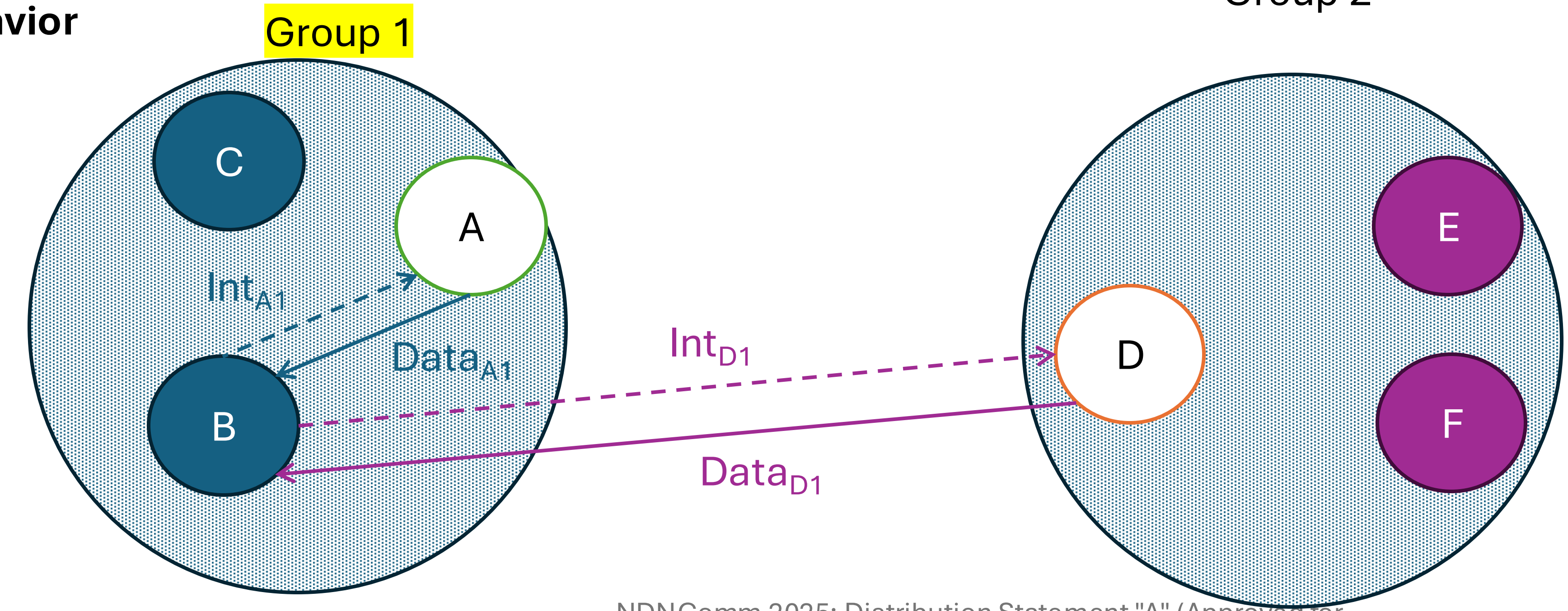
- Emulator: Mini-NDN [3]
- Mobility: reference point group mobility model [4].
- Application: modified version of ndn-traffic-generator [5]
- 30 runs for each forwarding strategy
- Optimal routing is pre-computed using node locations.

Experimental Parameters	Tested Value
Mobility Topology Size	500 m^2
Reference Point Parameters	100-meter group radius, 1.7-meter [6] reference point radius
Node Count	20
Node TX Power	21 dBm (Range of ~105 meters)
Network Bandwidth (Total)	2 Mbit/s
ASF Probe Interval	5s
Application Data Size	4000B
Traffic Patterns	"Configuration (Config)", "Update"
Tested Forwarding Strategy	ASF, Selective Backup Probing (SBP), Controlled Probe Propagation (CPP), Combination (Combo)

Configuration Traffic Model

- In each group, one node is designated as a producer for the “configuration” data.
- All other nodes (“clients”) request 10 new data unique to the consumer from each of these producers
- Each “client” node sends these requests this every 200 seconds, with 750ms between subsequent interests

CONFIG PATTERN: Node B (Client Node) Traffic Behavior



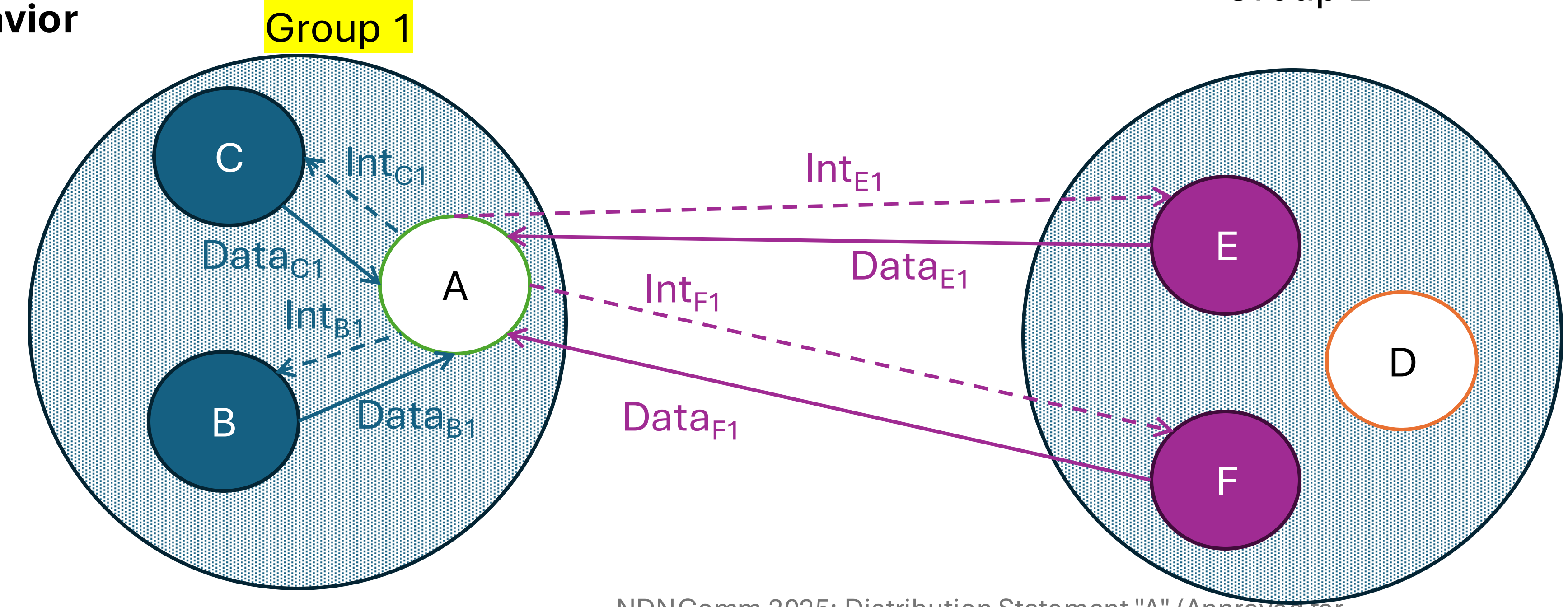
Group 1
Central Node: A
Client Nodes: B, C

Group 2
Central Node: D
Client Nodes: E, F

Update Traffic Model

- In each group, one node is designated as “central node” which produces configuration data
- Both “central” nodes request the same new data from each client node
- Each “central” node sends these requests this every 5 seconds, with 250ms between interests to different clients

UPDATE PATTERN: Node A (Central Node) Traffic Behavior



Group 1
Central Node: A
Client Nodes: B, C

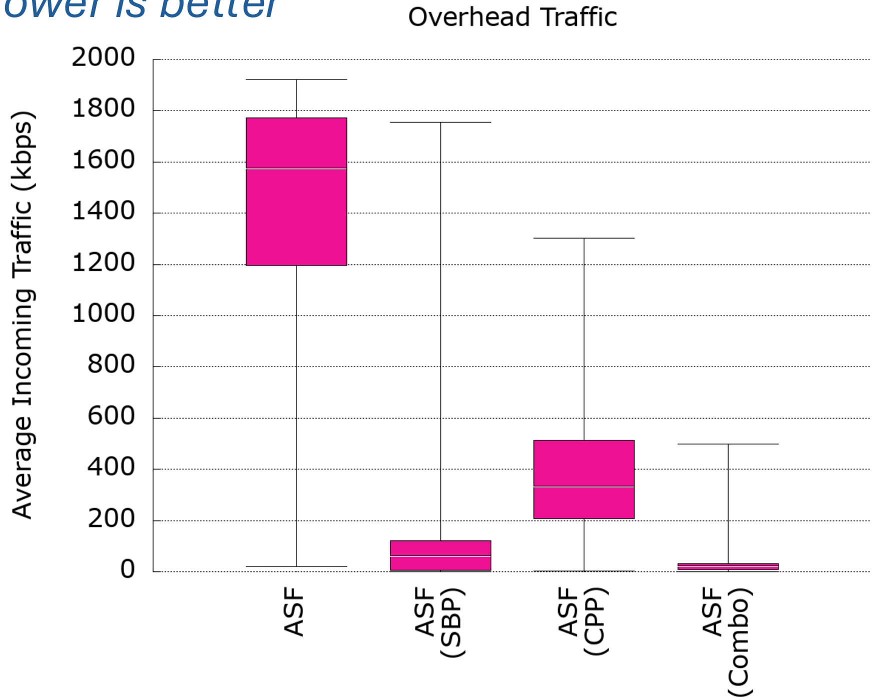
Group 2
Central Node: D
Client Nodes: E, F

Evaluation: Performance Metrics

- **Normalized Satisfaction Ratio**: For each run, take percentage of Interests from consumers that successfully retrieve matching Data packets and get the ratio with the optimal routing case
- **RTT**: median duration from when a consumer sends an Interest to when it receives the matching Data packet
  - Maintained per consumer-producer pair, we look at the distribution of these cases for the **Median** and **95th** percentile values
- **Traffic:** the distribution of the total incoming traffic per second for all nodes during the experiment
  - **Overhead:** Probe interests, duplicate data, lost data, Nacks, Link Manager traffic
  - **Application:** Application-generated interests, the first copy of a data to reach a consumer which requested it

Evaluation: Overhead

Lower is better

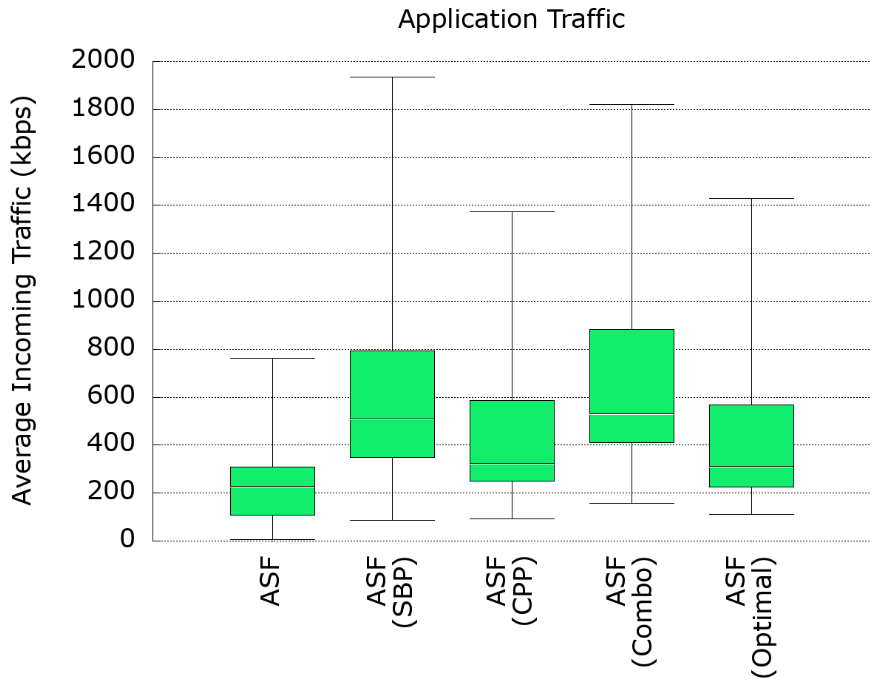


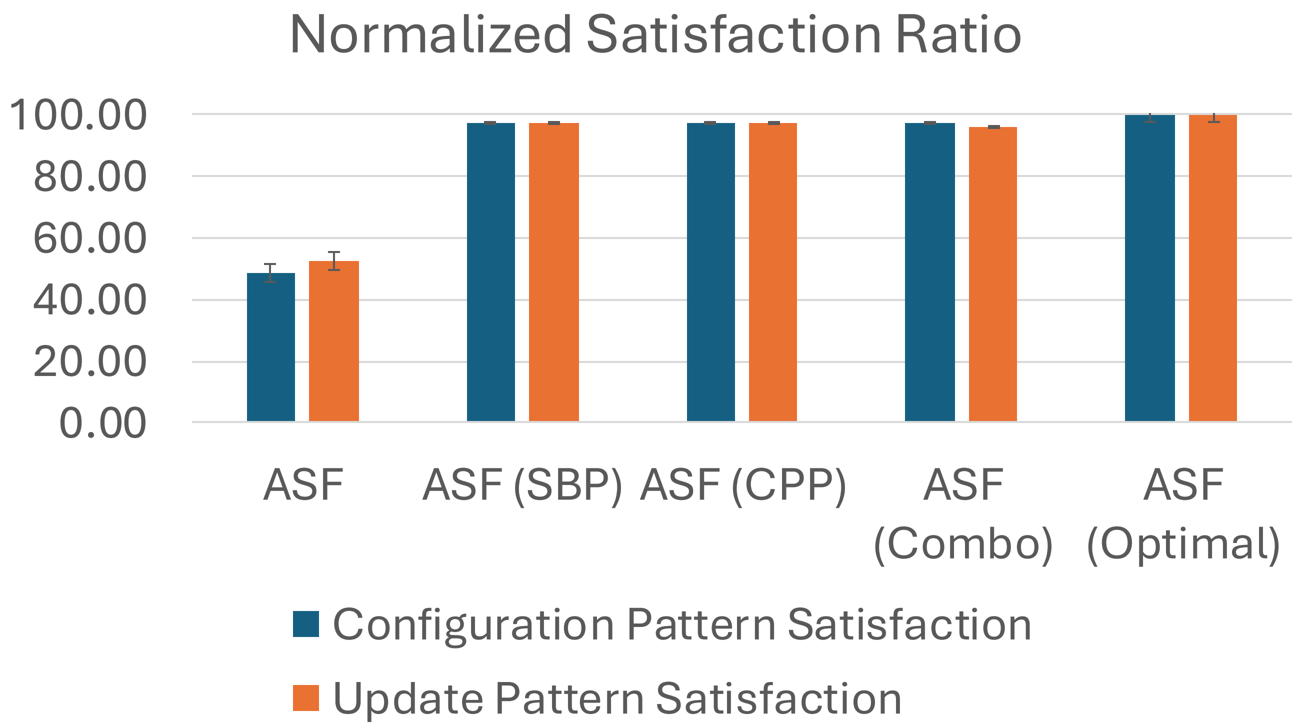
Overhead Traffic (kbps)	ASF	ASF (SBP)	SBP % Reduction	ASF (CPP)	CPP % Reduction	ASF (Combo)	Combo % Reduction
Median	1575.6	64.5	95.9	334.6	78.8	22.4	98.6
Max	1922.1	1753.9	8.8	1301.8	32.3	498.8	74.0

Observations:

- By combining the lower probe volume of the selective backup probing change and the restricted exponential growth of the controlled probe propagation change, the combo configuration consumes at most ~25% of the bandwidth capacity for overhead and has a median closer to ~1%.
- While our initial target was lower, this is still a very significant reduction given the minimal changes required.

Evaluation: Application Traffic



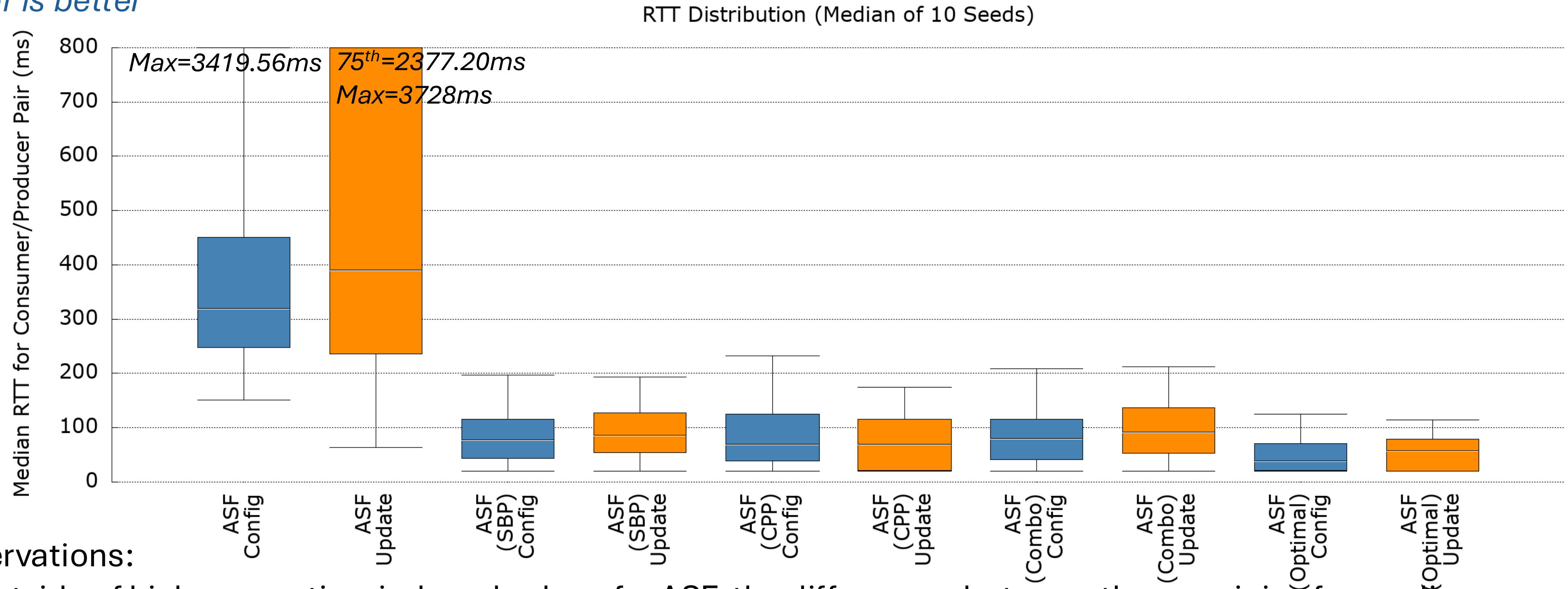


Observations:

- We can clearly observe that the overhead generated by ASF is causing congestion sufficient to prevent our application from functioning correctly. Reducing the ASF overhead via our changes allows us to reach levels of interest satisfaction close to the optimal case.
- We can also note the different factors of application traffic due to it counting multiple hops for the same packet; while ASF generates low application traffic due to minimal interest satisfaction, the CPP change shows close to the value in the optimal case due to lower hop counts, most likely from more proactive probing.

Evaluation: Median RTT

Lower is better

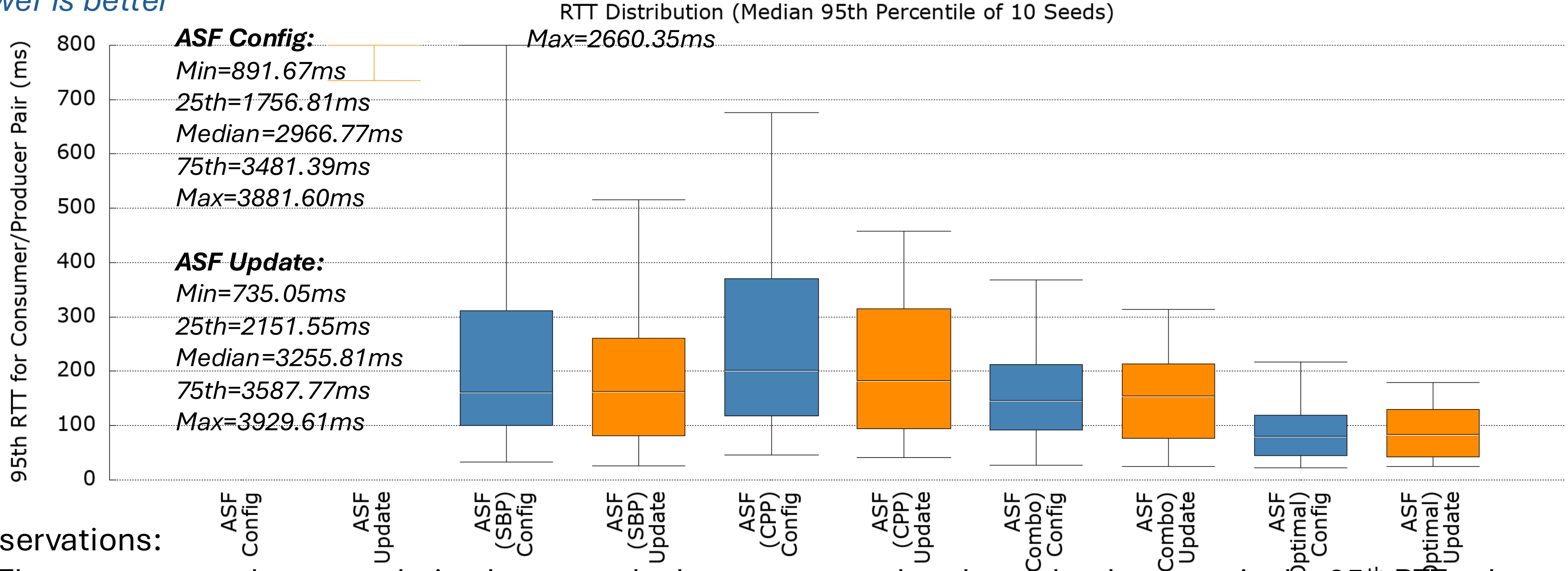


Observations:

- Outside of high congestion-induced values for ASF, the differences between the remaining forwarding methodologies are mostly fairly minor and generally within margin of error. However, the medians for the controlled probe propagation change are distinctly lower, most likely due to the more proactive probing in this case.
- The disproportionate ASF update pattern result likely stems from the fact the update pattern generates far more probes, which would exacerbate congestion significantly given the uncontrolled exponential growth.

Evaluation: 95th RTT

Lower is better



Observations:

- There appears to be a correlation between the lower max overhead and the decrease in the 95th RTTs observed; many of these outlier RTTs seem to stem from periods of queuing in high traffic. Decreasing the overhead would be expected to lighten this load.
- We notably observe consistently higher numbers for the configuration pattern outside of ASF; this is likely an artifact of the configuration traffic having a smaller sample size and being more easily skewed by individual periods of higher RTT.

Summary

- We investigated
  - Impacts of adhoc wireless on ASF strategy
  - Impacts of different changes to the ASF forwarding strategy on overhead generation
- Observations and conclusions
  - With the given application and topology, ASF is not able to function effectively under strict bandwidth limits due to congestion
  - Both selective backup probing and controlled probe propagation alone are effective methods to lower overhead through their different approaches to reducing ASF overhead
  - When combined, we can see median overhead generation as low as ~1% of the total bandwidth cap for our restricted case with minimal impact on other metrics in this test case
  - We hope to use this as a jumping off point for more broad research into the general usefulness of these changes

Future Work

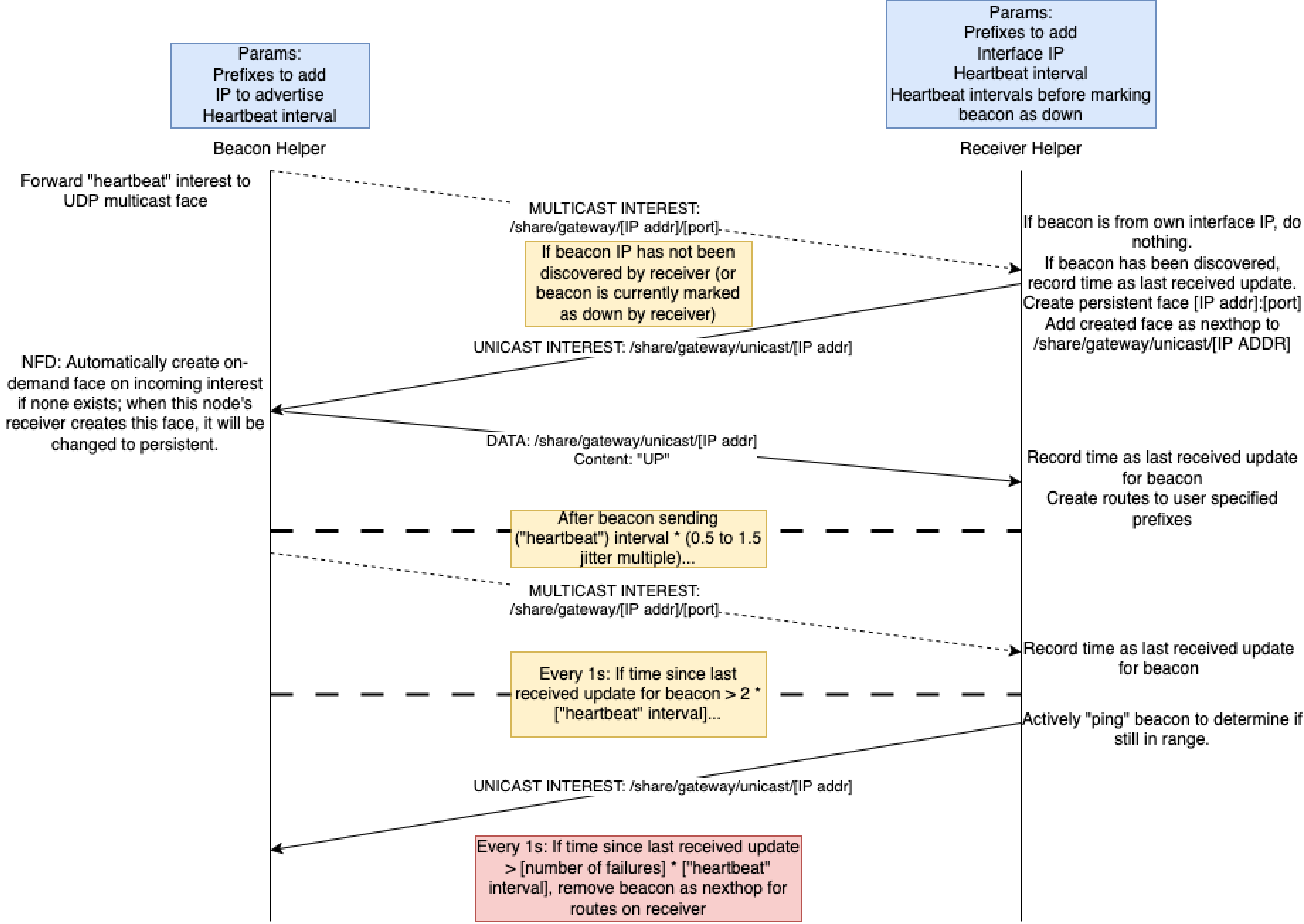
- We intend to test with more topologies and do further investigation on some of the changes we did not test
- We want to see if our proposed changes may have beneficial effects for wired topologies

References

- [1] Lan Wang, Alexander Lane, Constantin Serban, Jesse Elwell, Alex Afanasyev, and Lixia Zhang. 2023. Investigating the Synergy between Routing and Forwarding Strategy in NDN Networks. In Proceedings of the 10th ACM Conference on Information-Centric Networking (ACM ICN '23). Association for Computing Machinery, New York, NY, USA, 67–77. https://doi.org/10.1145/3623565.3623714
- [2] V. Lehman et al., An experimental investigation of hyperbolic routing with a smart forwarding plane in NDN. 2016 IEEE/ACM 24th International Symposium on Quality of Service (IWQoS), Beijing, China, 2016, pp. 1-10, doi: 10.1109/IWQoS.2016.7590394.
- [3] Mini-NDN Website, https://minindn.memphis.edu.
- [4] Xiaoyan Hong, Mario Gerla, Guangyu Pei, and Ching-Chuan Chiang. 1999. A group mobility model for ad hoc wireless networks. In Proceedings of the 2nd ACM international workshop on Modeling, analysis and simulation of wireless and mobile systems (MSWiM '99). Association for Computing Machinery, New York, NY, USA, 53–60. 10.1145/313237.313248
- [5] NDN Traffic Generator Github, https://github.com/named-data/ndn-traffic-generator.
- [6] Murtagh EM, Mair JL, Aguiar E, Tudor-Locke C, Murphy MH. Outdoor Walking Speeds of Apparently Healthy Adults: A Systematic Review and Meta-analysis. Sports Med. 2021 Jan;51(1):125-141. doi: 10.1007/s40279-020-01351-3. PMID: 33030707; PMCID: PMC7806575.

Backup Slides

Backup: Link Manager



Backup: Experiment Design - Precalculated Case

- Using node position, we can approximate the wireless topology as it changes
- Given that we know these numbers ahead of time, we can precalculate potential nexthops for any given periods and use them in a real run
- Our presumptions are the following:
  - We only compute the best nexthop to avoid probing
  - Due to running in real time, changes are only computed to the nearest millisecond
  - Nexthops should be less than 103.5 meters away; it’s likely that nodes farther away will have inconsistent behavior and may come in and out of range too often
    - We otherwise assume changes are non-transitory

Backup: ASF Design

- ASF (Adaptive SRTT-Based Forwarding) aims to find the shortest path available while adapting to network changes (Lehman et al).
- ASF maintains internal measurements of nexthops' SRTT and whether it recently received data primarily to rank nexthops to be used in forwarding; ASF will pick the top ranked nexthop without an out record, or the least recently used in the worst case.
- This is aided by "periodic probing":
  - Probing is used to test the performance of other nexthops.
  - ASF maintains a timer for each routing prefix.
  - When an interest is received that matches that prefix, if that timer has elapsed for the relevant prefix, it will send a copy of the interest to another potential nexthop if possible and reset the timer.
  - The nonce is refreshed to avoid triggering duplicate nacks, which allows us to get measurements for the full traversed path.
  - The top ranked nexthop is chosen if it's unmeasured. Otherwise, a face is chosen probabilistically, weighted towards higher ranked nexthops.

Backup: ASF Design – Probing (Flowchart)