Ad Hoc Networking Critical Features and Performance Metrics

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A mobile ad hoc network (MANET) is an autonomous collection of mobile users (nodes) that communicate over wireless links. Due to nodal mobility, the network topology may change rapidly and unpredictably over time. The network is *decentralized*, where network organization and message delivery must be executed by the nodes themselves. MANETs have a wide range of applications from military networks to emergency preparedness telecommunications.

In this document, critical networking features and performance metrics for assessing the behavior of an ad-hoc network are identified. Moreover, a strategy for computing the desired quantities is outlined. This document is organized as follows. In Section 1, critical ad-hoc networking features are identified. In Section 2, performance metrics to assess the behavior of MANETs are identified. In Section 3, an implementation strategy for computing the critical ad-hoc networking features is described, and finally in Section 4, an implementation strategy for computing the performance measures is described.

1 Critical Ad-Hoc Networking Features

Regardless of the application, there are certain critical features that can determine the efficiency and effectiveness of an ad-hoc network. These features can be categorized into *quantitative* features and *qualitative* features.

1.1 Quantitative Critical Features

- Network Settling Time - Time required for a collection of mobile wireless nodes to automatically organize itself and transmit the *first* task reliably. Settling time is extremely important when a network has not been in operation for a while, and then must start-up and send messages promptly.

- Network Join - Time required for an entering node or group of nodes to become integrated into the ad-hoc network.

- Network Depart - Time required for the ad-hoc network to recognize the loss of one or more nodes, and reorganize itself to route around the departed nodes.

- Network Recovery Time - Time required for the network to recover after a condition that dictates reorganization of the network. Specifically, (1) for a collapsed portion of the network, due to traffic overload or node failures, to become functional again once the traffic load is reduced or the nodes become operational or (2) for the network to reorganize due to node mobility and resume reliable communication.

- Frequency of Updates (Overhead) - In a given period, the number of control packets (bytes) or overhead bytes in a packet required to maintain proper network operation.

- Memory Byte Requirement - Storage space requirements in bytes, including routing tables and other management tables.
- Network Scalability Number - Number of nodes that the ad-hoc network can scale to and reliably preserve communication. The network should be able to scale to 10,000 nodes.

1.2 Qualitative Critical Features

- Knowledge of Nodal Locations - Does the routing algorithm require local or global knowledge of the network?
- Effect to Topology Changes - Does the routing algorithm need complete restructuring or incremental updates?
- Adaptation to Radio Communication Environment - Do nodes use estimation knowledge of fading, shadowing, or multiuser interference on links in their routing decisions?
- Power Consciousness - Does the network employ routing mechanisms that consider the remaining battery life of a node?
- Single or Multichannel - Does the routing algorithm utilize a separate control channel? In some applications, multichannel execution may make the network vulnerable.
- Bidirectional or Unidirectional Links - Does the routing algorithm perform efficiently on unidirectional links, e.g., if bidirectional links become unidirectional?
- Preservation of Network Security - Does the routing algorithm uphold the fidelity of the network, for example, *low probability of detection*, *low probability of intercept*, and security?
- QoS Routing and Handling of Priority Messages - Does the routing algorithm support priority messaging and reduction of latency for delay sensitive real time traffic? Can the network send priority messages/voice even when it is overloaded with routine traffic levels?
- Real-time Voice Services - Can the network support simultaneous real-time multicast voice while supporting routine traffic loads associated with situation awareness, and other routine services?
- Real-time Video Services - Can the nodes receive or transmit video on demand, while still supporting traffic levels associated with situation awareness, voice conversations, and other routine services?

2 Performance Metrics

2.1 Thread-Task Level Metrics

The following set of metrics will provide a good method for assessing a MANET algorithm: [Note that these metrics are computed at the thread level.]

- **Average Power Expended** - Average power expended (Watts) in a network in a given time period to complete a thread (task). This will include power expended in transmitting control messages and information packets.
- **Task Completion Time** - Time to complete a task in seconds. It is a measure of implicit complexity and overhead to complete a given task.

2.2 Diagnostic Packet Level Metrics

Diagnostic metrics characterize network behavior at the packet level.

- **End-to-End Throughput** - Average successful transmission rate. Measure of the number of packets successfully transmitted to their final destination per unit time.
- **End-to-End Delay** - Average time a packet takes to reach its destination.
- **Link Utilization** - Long term proportion of time or probability that there is transmission on the link.
- **Packet Loss** - Ratio of transmitted packets that may have been discarded or lost in the network. This will take into account packets that are discarded after several pre-determined attempts at retransmission, and packets that are lost due to looping. In addition, packet loss may be due to many factors including variable link quality, buffer overflow, and outdated routing information.

2.3 Scenario Metrics

These metrics describe the network environment and define the scenario.

- Nodal Movement/Topology Rate of Change - Average speed of nodes
- Number of Network Nodes
- Area Size of Network
- Density of Nodes per Unit Area
- Offered load and traffic patterns
- Number of Unidirectional Links

3 Implementation Strategy for Computing Critical Ad-Hoc Networking Features

3.1 Network Settling Time

The nodes of an ad-hoc network must dynamically discover one another and organize themselves into a functioning network capable of reliable communication. A meaningful metric to capture the ability of the network to do this is the *Network Settling Time*. Specifically, the Network Settling

Time is the time required for a collection of mobile wireless nodes to automatically organize itself and transmit the first task reliably.

The first task may be one of the following:

- Funnelcast - A SITREP from each node member to another designated member. For example, a squad reporting in its location and status to a squad leader following a parachute landing.
- Multicast - A multicast voice to all squad members. For example, a squad leader issuing a command or point man issuing a warning.
- Unicast - A single message to another single address. For example, a call fire or sensor to shooter transaction.

The Network Settling Time for the above three cases will be determined for different network topologies. The network topology may be one of the following:

- Fully Connected Stationary Network - Any node can communicate directly with any other node in the network (dense network).
- Strongly Connected Stationary Network - Any node can communicate with any other node in the network within two hops. All nodes have at least two neighbors.
- Weakly Connected Stationary Network - Some nodes may have only one neighbor and some nodes may be separated by up to five hops.
- Strongly Connected Mobile Network - Added nodal mobility.
- Weakly Connected Mobile Network - Added nodal mobility
- Mobile Network Transitioning from a Strongly Connected Network to a Weakly Connected network.

REQUIRED

- Specific layouts for the six topologies.
- Specific task message formats (size and structure) for a funnelcast SITREP message, unicast message, and multicast message.

3.2 Network Join

A mobile ad-hoc network must be able to accommodate a new node or group of nodes into the network and continue efficient operation. A meaningful metric to access this ability is the *Network Join Time*. Specifically, the Network Join Time is the time required for an entering node or group of nodes to become integrated into the ad-hoc network and participate in the routing functions of the network.

The following network configurations will be considered (see Section 3.1 for a description):

- Fully Connected Stationary Network
- Strongly Connected Stationary Network

- Weakly Connected Stationary Network
- Strongly Connected Mobile Network
- Weakly Connected Mobile Network
- Mobile Network Transitioning from a Strongly Connected Network to a Weakly Connected network.

In each configuration, two situations will be considered. First, a single new node will enter the network in a specified location. Second, a group of 5 nodes will enter the network in pre-determined locations. In each case, the Network Join Time will be computed as the time it takes for the entering node(s) to successfully transmit a funnelcast SITREP to a designated member, e.g., platoon leader.

REQUIRED

- Specific layouts for the six topologies (also required in Section 3.1).
- Message format for a SITREP message (also required in Section 3.1).
- Location of the entering nodes.

3.3 Network Depart

A mobile ad-hoc network must be able to accommodate the loss of one or more nodes from the network and continue efficient operation. A meaningful metric to access this ability is the *Network Depart Time*. Specifically, the Network Depart Time is the time required for the network to recognize the loss of one or more nodes, and reorganize itself to route around the departed nodes.

The following network configurations will be considered (see Section 3.1 for a description):

- Fully Connected Stationary Network
- Strongly Connected Stationary Network
- Weakly Connected Stationary Network
- Strongly Connected Mobile Network
- Weakly Connected Mobile Network
- Mobile Network Transitioning from a Strongly Connected Network to a Weakly Connected network.

In each configuration, two situations will be considered. First, a single centrally located node will depart the network. This will give a worst-case analysis, since this case will require the most reorganization from the network. Second, a group of 5 nodes will depart the network. In each case, the Network Depart Time will be computed as the time it takes for the network to reorganize itself and for each node to successfully transmit a funnelcast SITREP to a designated member, e.g., platoon leader.

REQUIRED

- Specific layouts for the six topologies (also required in Section 3.1).
- Message format for a SITREP message (also required in Section 3.1).
- Location of departing nodes.

3.4 Network Recovery Time

Dynamic conditions in a mobile ad-hoc network will require reorganization of the network. Portions of a mobile ad-hoc network may collapse or become inoperational due to excess traffic or mechanical node failures. Moreover, since the nodes are moving, the network topology is constantly changing either in a predicted and uniform fashion, or totally unpredictably. A meaningful metric to capture the ability of the network to reorganize itself and resume reliable communication in the network is *Network Recovery Time*. Specifically, Network Recovery Time is the time required for a network to reorganize itself and resume reliable communication after (1) a portion of the network collapses due to traffic overload or node failures, or (2) the topology changes due to nodal mobility and variable link quality.

The following network configurations will be considered (see Section 3.1 for a description):

- Fully Connected Stationary Network
- Strongly Connected Stationary Network
- Weakly Connected Stationary Network
- Strongly Connected Mobile Network
- Weakly Connected Mobile Network
- Mobile Network Transitioning from a Strongly Connected Network to a Weakly Connected network.

In order to exercise the case (1), for each configuration, a portion of the network (5 connected nodes) will be stressed by two methods:

- Traffic Overload - The traffic generation rate at the 5 connected nodes will be increased in increments until the portion of the network becomes saturated and collapses. Once saturation is reached, the traffic load will be reduced incrementally until a funnelcast SITREP message by each of the 5 nodes can be transmitted successfully.
- Node Failures - 5 connected nodes will be turned off to simulate node failures. This is similar to the scenario for Network Depart, with the nodes being connected. The nodes will be turned on again. The time until a successful funnelcast SITREP message can be transmitted by each of the 5 nodes will be computed.

In order to exercise case (2), for the three mobility configurations above, the network will be subject to the following mobility patterns (If specific mobility patterns can be extracted from SEAMLSS, these patterns can also be used):

- Uniform Pattern - Nodes move at constant speeds in an organized pattern.
- Random Walk - Nodes move with random speeds in a random

REQUIRED

- Specific layouts for the six topologies (also required in Section 3.1).
- Message format for a SITREP message (also required in Section 3.1).
- Location of the 5 connected nodes.
- Uniform mobility patterns.
- Random walk mobility patterns.

3.5 Frequency of Updates - Overhead

In a mobile ad-hoc network, control messages/overhead are necessary to disseminate necessary information for network organization and routing execution. The amount of overhead necessary, however, will depend on the protocols being used. A meaningful metric to capture the overhead required for a protocol is the *Frequency of Updates - Overhead*. Specifically, the Frequency of Updates - Overhead is the amount of overhead information measured in bytes in a given period that is required to maintain proper network operation. The amount of overhead required will implicitly depend on the network configuration, i.e., a sparse network may require more exchange of control information than a dense network.

The following network configurations will be considered (see Section 3.1 for a description):

- Fully Connected Stationary Network
- Strongly Connected Stationary Network
- Weakly Connected Stationary Network
- Strongly Connected Mobile Network
- Weakly Connected Mobile Network
- Mobile Network Transitioning from a Strongly Connected Network to a Weakly Connected network.

For each configuration, the Frequency of Updates - Overhead will be measured at two different stages of network operation:

- Initialization - From network startup until the Network Settling Time (see Section 3.1), the bytes of overhead exchanged in the network will be computed.
- Maintenance - For a period of X seconds during stable network operation, the bytes of overhead exchanged in the network will be computed.

These two network stages will capture the overall overhead of a protocol since some protocols may have more expensive byte overhead in one stage of network operation than the other.

REQUIRED

- Specific layouts for the six topologies (also required in Section 3.1).
- The interval X - which can be determined analytically or empirically.

3.6 Memory Byte Requirement

In a mobile ad-hoc network, routing paths are determined by the nodes themselves and hence, there are memory storage requirements imposed on all nodes. The amount of storage necessary will depend on characteristics of the routing protocol, e.g, hop-by-hop routing vs. source routing and proactive routing vs. reactive routing. A meaningful metric to capture the amount of storage required for a protocol is the *Memory Byte Requirement*. Specifically, the Memory Byte Requirement is the amount of memory storage required in bytes to store routing tables, neighbor tables, and other management tables.

The following network configurations will be considered (see Section 3.1 for a description):

- Strongly Connected Stationary Network
- Strongly Connected Mobile Network

These configurations will provide a worst case analysis since dense networks will require more entries in routing and neighbor tables.

REQUIRED

- Specific layouts for the two topologies (also required in Section 3.1).

3.7 Network Scalability Number

A mobile ad-hoc network should be able to scale in number of nodes and still provide efficient functionality. A meaningful metric to capture this ability is the *Network Scalability Number*. Specifically, the Network Scalability Number is the number of network nodes that the ad-hoc network can scale to and reliably preserve communication.

The following network configurations will be considered (see Section 3.1 for a description):

- Fully Connected Stationary Network
- Strongly Connected Stationary Network
- Weakly Connected Stationary Network
- Strongly Connected Mobile Network
- Weakly Connected Mobile Network
- Mobile Network Transitioning from a Strongly Connected Network to a Weakly Connected network.

For each configuration, the number of nodes will be increased by $N = 100$ nodes at a time. (The value of N can be modified based on feedback from experiments.) For each increment, a multicast voice message will be transmitted by a designated node, e.g, platoon leader. Each node that receives the transmission will acknowledge the packet through the acknowledgment mechanisms provided - either passive acknowledgments or active acknowledgments. The largest number of nodes that can function reliably by successfully transmitting multicast voice messages will be computed as the Network Scalability Number.

REQUIRED

- Specific layouts for the six topologies (also required in Section 3.1).
- Multicast voice message format (also required in Section 3.1).

3.8 Qualitative Critical Features

The performance of a mobile ad-hoc network depends also on the qualitative critical features identified in Section 1.2. These features provide a global assessment of the network and do not depend on the type of network topology or messages being transmitted. Hence, for simplicity the following network will be considered:

- Strongly Connected Stationary Network where each node transmits a funnelcast SITREP message.

It may be also possible to determine the qualitative critical features by a static analysis of the network specifications.

REQUIRED

- Specific layout for the network topology (also required in Section 3.1).
- Funnelcast SITREP message format (also required in Section 3.1).

4 Implementation Strategy for Computing Performance Metrics

4.1 Thread-Task Level Metrics

4.1.1 Average Power Expended

The average power expended in the network is highly dependent on the hardware utilized. A protocol may perform efficiently on a particular radio platform and inefficiently on another. Hence, a simulation will be executed for each radio node architecture provided in SEAMLSS, i.e., WL, HMT, and IEEE 802.11.

The average power expended will be computed as the power utilized in

- transmitting information packets,
- transmitting control packets,

- receiving information packets, and
- receiving control packets.

The power expended in sending information and control packets is simply the transmitter power utilized. The power expended in receiving packets is difficult to quantify precisely. As an initial approach, a cost of Y will be charged for receiving an information packet, and a cost of $Y/2$ will be charged for receiving a control packet. These costs may be modified if necessary based on results from experiments. The above power costs should be computed for every transmission and reception in a thread-level task in SEAMLSS.
REQUIRED: An appropriate cost value for Y.

4.1.2 Task Completion Time

The time to complete a given task is computed in SEAMLSS.

4.2 Diagnostic Packet Level Metrics

Since the diagnostic metrics are packet level, certain minor additions must be made to either SEAMLSS or the interfacing simulation environment (PARSEC, OPNET, NS-2, CPT) in order to obtain the necessary output statistics.

4.2.1 End-to-End Throughput

Each time a network node successfully receives an information packet, a global counter tallying the number of correctly received information packets is incremented. The global counter will be an integer state variable. The end-to-end throughput τ can then be computed by

$$\tau = (Successfully\ Received\ Packets)\ /\ (Simulation\ Time\ Elapsed)$$

4.2.2 End-to-End Delay

A packet should be time stamped when it is generated. When a packet reaches its final destination, the end-to-end delay δ can be computed by

$$\delta = (Simulation\ Time\ at\ Reception)\ -\ (Simulation\ Time\ at\ Generation)$$

4.2.3 Link Utilization

A "clock" must be maintained for each link. The "clock" is a counter that keeps track of the amount of time that a link is being used. Every time a transmission occurs on the link, the time of use must be recorded and accumulated in the link "clock". The link "clock" can be a float state variable. The link utilization ρ can then be computed by

$$\rho = (Link\ Utilization\ Clock)\ /\ (Simulation\ Time\ Elapsed)$$

4.2.4 Packet Loss

Each time a network node successfully receives an information packet, a global counter tallying the number of correctly received information packets is incremented. (This is the same counter for the end-to-end throughput). Similarly, each time a network node transmits an information packet, a global counter tallying the number of transmitted packets is incremented. (This is also the offered load to the network.) These global counters will be integer state variables. The packet loss κ can then be computed by

$$\kappa = (Successfully\ Received\ Packets)\ /\ (Total\ Transmitted\ Packets)$$

4.3 Scenario Metrics

These metrics describe the network and are easily extracted from the SEAMLSS simulation environment.