The Pulse Protocol:
Mobile Ad hoc Network Performance Evaluation

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Abstract

We present a performance evaluation of the Pulse protocol operating in a peer-to-peer mobile ad hoc network environment. The Pulse protocol utilizes a periodic flood (the pulse*) initiated by the* pulse source *to provide both routing and synchronization to the network. This periodic pulse forms a pro-actively updated spanning tree rooted at the pulse source. Nodes communicate by forwarding packets through this tree. The main disadvantage of this tree traversal routing is that the paths are less direct than traditional shortest path routing. However, in exchange, drastically increased scalability with respect to mobility, number of flows, and node density is achieved. In addition, nodes are able to synchronize with the periodic pulse, allowing idle nodes to power off their radios a large percentage of the time when they are not required for packet forwarding. This results in substantial energy savings. Through simulation we explore the performance of the protocol with respect to packet delivery ratio, delay, and energy efficiency in peer-to-peer mobile ad hoc networks.*

1. Introduction

The Pulse protocol [3] was originally presented as an energy efficient multi-hop infrastructure access routing protocol. In that work, nodes in the network tracked the least cost path to the nearest gateway and peer-to-peer traffic was assumed to be minimal. Under the infrastructure model, the protocol exhibited excellent performance with regard to mobility, scalability, and energy efficiency. This work evaluates the performance of the Pulse protocol under the more general peer-to-peer mobile ad hoc network model in order to determine if these desirable properties are preserved.

Typically, on-demand protocols such as DSR [12] and AODV [14], or proactive protocols such as OLSR [7] and TBRPF [13] have been preferred for peer-to-peer mobile ad hoc networks. Each of these protocols is an example of the *direct routing* strategy, where the route from source to destination is constructed by finding the shortest path using a given metric.

The Pulse protocol breaks from this tradition by employing a *tree routing* strategy. A spanning tree is constructed by a flood initiated by the *pulse source*. Packets are then routed using a tree traversal. In other words, a packet originating from a source will be sent up the tree (towards the pulse source) until it reaches a node that is a parent of both the source and destination, then the packet is sent down the tree to the destination. Routing trees have been commonly used for multi-cast and broadcast traffic, but using trees for unicast traffic is uncommon. While this strategy results in paths that are longer than the direct routing strategy, it has inherent scalability benefits.

For example, the proactive pulse flood provides scalability to high levels of mobility. As the mobility level increases, many failures begin to occur throughout the network. In the Pulse protocol, all broken routes are repaired simultaneously within one pulse interval using one flood. In contrast, an on-demand protocol may initiate one flood for every broken active route, and a proactive link-state protocol may generate one flood per link failure. As the number of failures increases, this results in congestion due to the additional routing overhead, limiting the scalability of these protocols to high levels of mobility.

In addition, the Pulse protocol offers integrated energy saving functionality. The periodic pulse also serves as a network wide synchronization protocol. When nodes are not required for packet forwarding, they may power off their radios for the time between pulse floods. This results in substantial energy savings and drastically increases the lifetime of the network.

Our Contribution. We present a performance evaluation of the Pulse protocol under a general peer-to-peer mobile ad hoc network model. In this model, all nodes are mobile and no assumption about the location of the pulse source is made. In addition the power consumption of the pulse source must be included in the analysis. Through simulation we explore the performance of the Pulse protocol by comparing it with DSR, an established on-demand mobile ad hoc networking protocol. We evaluate both protocols under a wide range of conditions by varying mobility, network density, network load, and number of flows. The delivery ratio, end-to-end delay, and energy consumption are evaluated.

2. Pulse Protocol

In this section we provide a review of the Pulse protocol features and operation. A more detailed specification of the protocol operation is provided in [3].

2.1. Routing

The protocol design is centered around a flood (the *pulse*) which is periodically sent at a fixed *pulse interval*. This pulse flood originates from the *pulse source* and propagates through the entire ad hoc network. This rhythmic pulse serves two functions simultaneously. It serves as the primary routing mechanism by periodically updating each node in the networks route to the pulse source. Each node tracks the best route to the pulse source by remembering only the node from which it received a flood packet with the lowest metric. The propagation of the flood forms a loop free routing tree rooted at the pulse source. In addition, it is used to provide network-wide time synchronization.

If a node needs to send and receive packets, it responds to the flood with a reservation packet. This reservation packet is sent up the tree to the pulse source. The reservation packet contains the address of the node making the reservation, and is used to setup reverse routes at all nodes on the path between the pulse source and the sending node. This reservation mechanism operates similarly to the route response mechanism used in AODV [14]. Note that it is not necessary for a node to send a reservation packet in response to the flood, unless it is actively transferring packets. A node that is actively communicating must send a reservation packet for every pulse it receives to keep the reverse route fresh. When a node has not sent or received packets for at least a complete pulse interval, it no longer sends a reservation packet in response to the pulse.

When a node overhears a reservation packet it creates reverse route entries through the node which it heard the reservation from. This mechanism allows a node to have routes to all active nodes in both its sub-tree and the sub-tree of its neighbors. This can allow peer-to-peer packets to take a *shortcut* across the routing tree, reaching the destination in fewer hops.

In the event that packets arrive at the pulse source destined for a node that does not have a currently active path, the pulse source will page the node on the next pulse flood. Paging simply involves placing the node's id in the pulse flood packet. When a node receives a flood packet containing its id, it responds with a path reservation packet. This activates the path and sets up the route from the pulse source to the node. Thus data packets can be delivered to nodes that are not currently active. This can occur when data has not been sent for a while on an open connection, or when a new connection is being initiated to an ad hoc node (from either the infrastructure network or another ad hoc node).

2.2. Energy Saving

The Pulse protocol uses the time synchronization provided by the flood to create a fixed period of time during which all nodes in the network are active. In addition to providing routing, the flooded pulse packets carry time stamps which are used to establish network wide time synchronization. During this *pulse period*, the pulse flood propagates, and nodes can reply with reservation packets. Since a node that does not send or forward a reservation packet will have no packet forwarding responsibilities until the next pulse occurs, it may place its radio in sleep mode until the next pulse period begins. This node deactivation is what allows the Pulse protocol to conserve power.

During the reservation period nodes promiscuously listen to the reservation packets. If they overhear a reservation packet then they know that they are in range of a node which will be active during the next period. Thus any node that neighbors an active path can perform a *fast activation* if they have a data packet to send, meaning they turn on in the middle of the data transfer period and forward data to their active neighbor. Fast activation eliminates the need for nodes to wait until the next pulse interval, resulting in reduced activation delay.

The Pulse protocol requires that nodes are always powered on during the pulse period and that no data packets are sent during this time interval. The pulse interval used for simulations was 1 seconds, of which 152 milliseconds were required for the pulse period. This ratio results in the protocol consuming 15% of the available network resources. A number of factors come as a result of this decision. The total bandwidth available to nodes in the network is limited to 85% of the actual bandwidth as a result of this fixed overhead. These timings determine the duty cycle of idle nodes in the network. Nodes which are not communicating or forwarding packets are required to be active 15% of the time to participate in the protocol, but can place their radios in a sleep mode for the remaining 85% of the time.

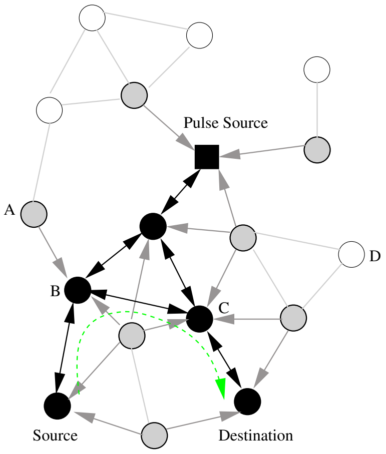


Figure 1. Pulse Protocol Routing Example

2.3. Protocol Discussion

Figure 1 shows an example of the information maintained by the Pulse protocol. Since there is an active flow from the node labeled source to the node labeled destination, each node sends a reservation packet up the tree to the pulse source in response to the pulse flood. Nodes that have forwarded a reservation stay on and are colored black. The rest of the nodes in the network may turn off until the next pulse. Nodes that overheard a reservation (or are adjacent to the pulse source) may perform fast activation and are colored grey. Node A can perform fast activation since it was able to overhear B forward the source's reservation packet. Node D is an example of a node that did not overhear any reservation packets and would need to wait for the next pulse period to activate.

Scalability: One unique quality of the Pulse protocol is its inherent scalability according to many metrics. Since all other routing traffic aside from the periodic pulse is unicast, the route acquisition process creates only local traffic on the network. In contrast, traditional on-demand protocols must flood and re-flood the network for each active connection in order to establish and maintain routes.

Scalability to high levels of mobility is provided by the proactive pulse flood. As the mobility level increases, many route failures begin to occur throughout the network. In the Pulse protocol, all broken routes are repaired simultaneously within one pulse interval using one flood and one unicast for every active node. In contrast, an on-demand protocol may initiate one flood and one unicast for every broken route, a proactive link-state protocol may generate one flood per link failure. As the number of failures increases, this results in congestion due to the additional routing overhead, limiting the scalability of these protocols to high levels of mobility. In addition, if a hello protocol is used instead of link layer feed back, a link failure is typically detected when two consecutive hello packets have been missed. The pulse interval used in our simulations is one second, which allows the fault to be repaired before a typical hello protocol would even detect it.

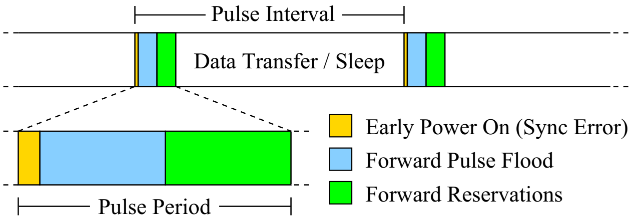


Figure 2. Pulse Protocol Timing Diagram

While the overhead of many routing protocols, particularly those which function on-demand, increases as a result of increased node mobility, route failures, high node density, or a sudden increase in the number of traffic sources, the Pulse protocol's overhead remains fixed. The effectiveness of this technique is best seen through our simulation results in Section 3.

Activation Delay: The Pulse protocol exhibits several features of both proactive and on-demand protocols. While the Pulse flood pro-actively maintains a route from all nodes in the network to the pulse source, reverse routes are established on-demand, but maintained pro-actively. Similarly to other on-demand protocols, the establishment of a route can result in activation delay. In the Pulse protocol, the worst case activation delay to establish a peer-to-peer connection is two pulse intervals (2 seconds with a one second pulse interval). The worst case occurs when a node receives a packet from the application layer immediately after the current pulse period ends. The node would need need to wait a full interval before it could send a reservation during the next pulse period. After the pulse period it can begin transmitting data. However, when the pulse source receives the data, it may have to wait an additional pulse interval until the next pulse period in order to page the destination.

Routing Metrics: In recent work a number of new routing metrics have been proposed: Medium Time Metric (MTM)[2], Expected Transmission Count (ETX)[8], and Weighted Cumulative Expected Transmission Time (WCETT)[10]. These metrics have been shown to provide higher performance [9] with respect to both throughput and path reliability in multi-hop networks. All of the proposed metrics require the ability to track link quality information (speed, signal, and/or reliability). The pro-active component of the Pulse Protocol already tracks time synchronization and maintains routing tables; and is easily extended to gather the additional statistics required by these new routing metrics with no additional routing overhead.

Table 1. Pulse Protocol Parameters

Pulse Interval	1	sec
Early Power On (Sync Error)	12	msec
Forward Pulse Flood	70	msec
Forward Reservations	70	msec
Flood Retransmission Delay	4	msec
Flood Retransmission Jitter	1	msec

3. Simulation

3.1. Simulation Setup

This work uses the Pulse protocol implementation from [3] which runs in version 2.1b9a of NS2[1]. The simulation setup used in this work is intended to model a peer-to-peer mobile ad hoc network. The pulse source operations are performed by a randomly selected node, which is randomly placed, and under the same mobility model as the other nodes in the simulation. Unlike previous work [3], the pulse source is not assumed to be in the center of the network and is not the communication end point of all connections. All connections are peer-to-peer between randomly selected nodes. Parameters including number of nodes, node mobility, and traffic load were all varied to explore the performance of the protocols under a variety of different network conditions. All simulations use a network size of 1 km by 1 km and are run for 300 virtual seconds. 802.11 radios with a bandwidth of 2 Mbps and a nominal range of 250 meters are used. DSR is configured with the NS2 default options. Timing parameters for the Pulse protocol (see Table 1) are based on the experiments conducted in [3], but have been modified for the peer-to-peer network model.

A random exponentially distributed on/off traffic model is used which allows every node in the network to be a potential traffic source and destination, as opposed to a small fixed set of nodes. This exponential on/off model functions as follows: each flow stays off for an exponentially distributed length of time with a specified average, then comes on and sends at a fixed rate (10 kbps using 512 byte packets) for an exponentially distributed amount of time with an average of ten seconds, then repeats the process. Flows between all pairs of nodes are created. This traffic model has a number of properties. By adjusting the average off time, any average offered load can be achieved. In addition, since the load is composed of fixed rate flows, setting the offered load simultaneously determines the average number of active flows (e.g. setting an offered load of 0.2 Mbps results in an average of 20 flows active at a time). Finally, this on/off scheme continuously changes the set of active flows. The average on time and average number of active flows determines the rate of change (e.g. an offered load of 0.1 Mbps and an average on time of 10 seconds results in and average of 10 active flows with one flow changing per second).

A random way-point mobility model is used in the simulations. In order to achieve more steady mobility characteristics [17], nodes select a speed uniformly between 10% and 90% of the given “max” speed. In addition, 300 virtual seconds of mobility are generated before the start of the simulation. When the simulation starts, nodes are already in motion. This allows the average speed and node distribution to stabilize. In the simulations, pause time is set to zero and the level of mobility is controlled by modifying the maximum speed parameter.

Table 2. 802.11b Card Power Consumption

Transmit	Receive	Idle	Sleep
1.3272 W	.96696 W	.84372 W	.06636 W

3.2. Power Consumption Model

In order to analyze the power efficiency of routing protocols, it is important to first understand exactly how power is consumed by wireless interfaces. In this work we will specifically be referring to 802.11 wireless adapters. The wireless interface is capable of being in four possible operational states, each of which consumes power at a specific rate. The least power consuming state is the *sleep state*. While in the sleep state the wireless card itself is still consuming a small amount of power, but the radio (which typically consumes the most power) is turned off. While in this state, the card is unable to send or receive packets and has no knowledge of activities taking place on the medium. Since only the radio is powered off, the card can switch the radio off and on quickly. If the card is completely powered off (not just the radio) the reactivation time is much longer.

The wireless card can also be in an *idle state*, meaning its radio is powered on, but it is not currently sending or receiving data. On-demand routing protocols typically spend a great deal of time in this state, since they need to be continuously ready to receive route requests. While in the idle state the card is continuously monitoring the medium sensing for a carrier signal which would cause it to enter the receiving state. The card is in the *transmit* or *receive* state when it is actively sending or receiving.

According to the power consumption measurements for commonly available 802.11b cards [11] (Table 2), the power consumption in the sending or receiving state is not much more than the power consumption in the idle state, while the sleep state consumes significantly less power. The idle state consumes only 36% less power than continuously transmitting. The sleep state however consumes 95% less power then continuously transmitting. As a result, in order to achieve maximum power savings a protocol must utilize the sleep state as frequently as possible.

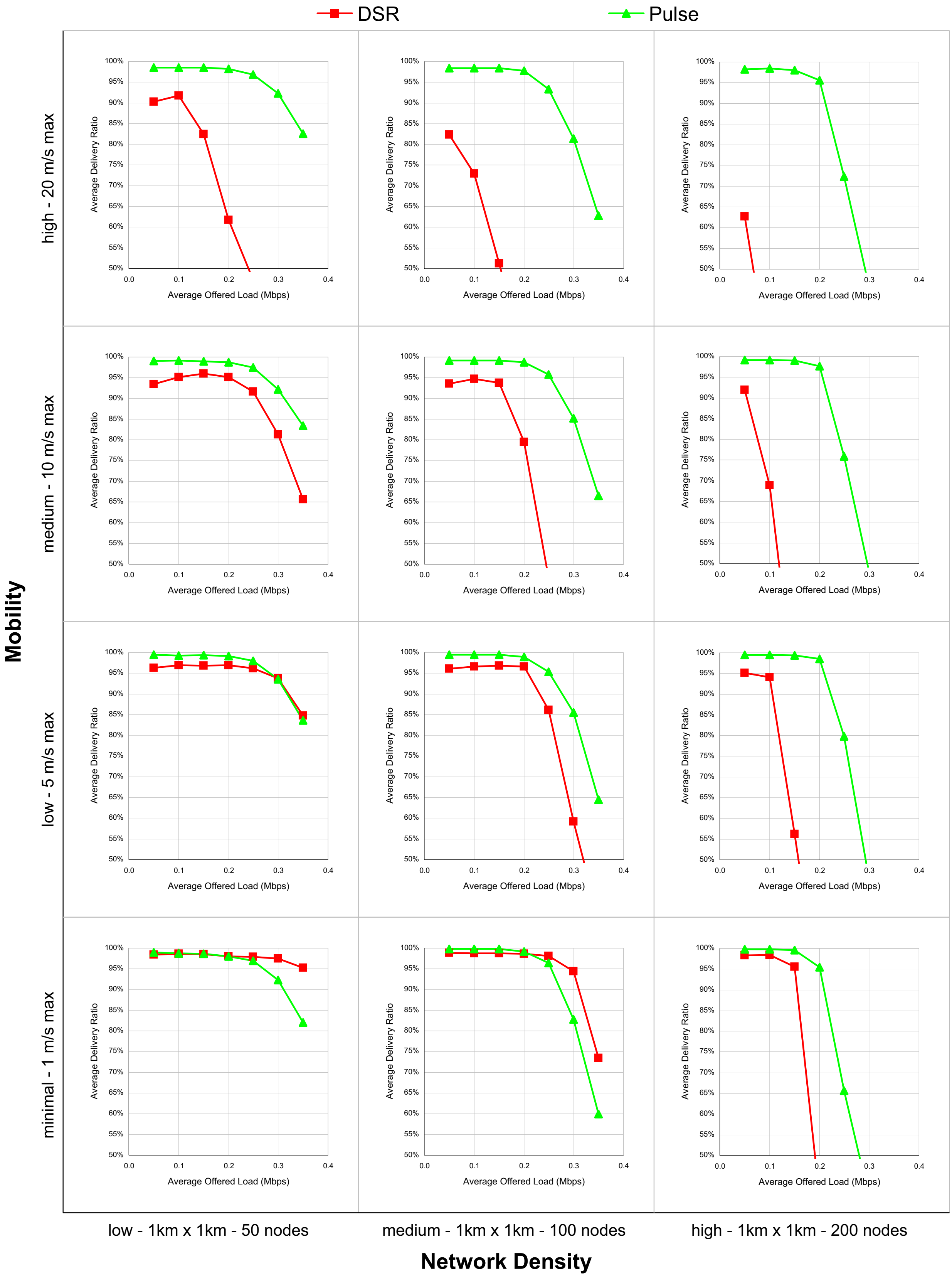
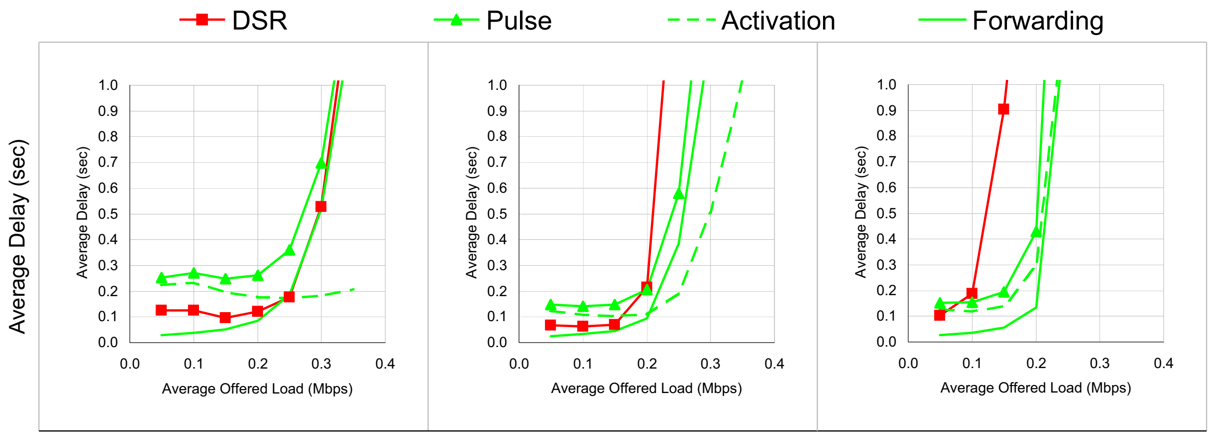


Figure 3. Delivery ratio results using random way-point mobility and exponential on/off traffic



low - 1km x 1km - 50 nodes medium - 1km x 1km - 100 nodes high - 1km x 1km - 200 nodes

Figure 4. Delay in the 1km x 1km - 5 m/s max scenario

3.3. Delivery Ratio Evaluation

In this experiment our goal is to evaluate the delivery ratio of the Pulse protocol by comparing it with DSR. Figure 3 shows several dimensions of information regarding the performance of the tested routing protocols. The page x-axis shows three network densities. The page y-axis shows four levels of mobility. For each combination of network density and mobility, a sub-graph is shown. Each sub-graph x-axis shows the average offered load produced by the on/off traffic generators, and each sub-graph y-axis shows the resulting average delivery ratio. This figure is setup so that the degree of difficulty increases as the scenario is located further up and more to the right on the page.

The most striking feature apparent in these results is the performance of the Pulse protocol under high mobility (top of the page). These results illustrate the effectiveness of the Pulse protocol design. Its proactive route maintenance and low fixed routing overhead, even under a large number of simultaneous faults, yields delivery ratios that are only minimally reduced even at the highest simulated levels of mobility (20 m/s max speed).

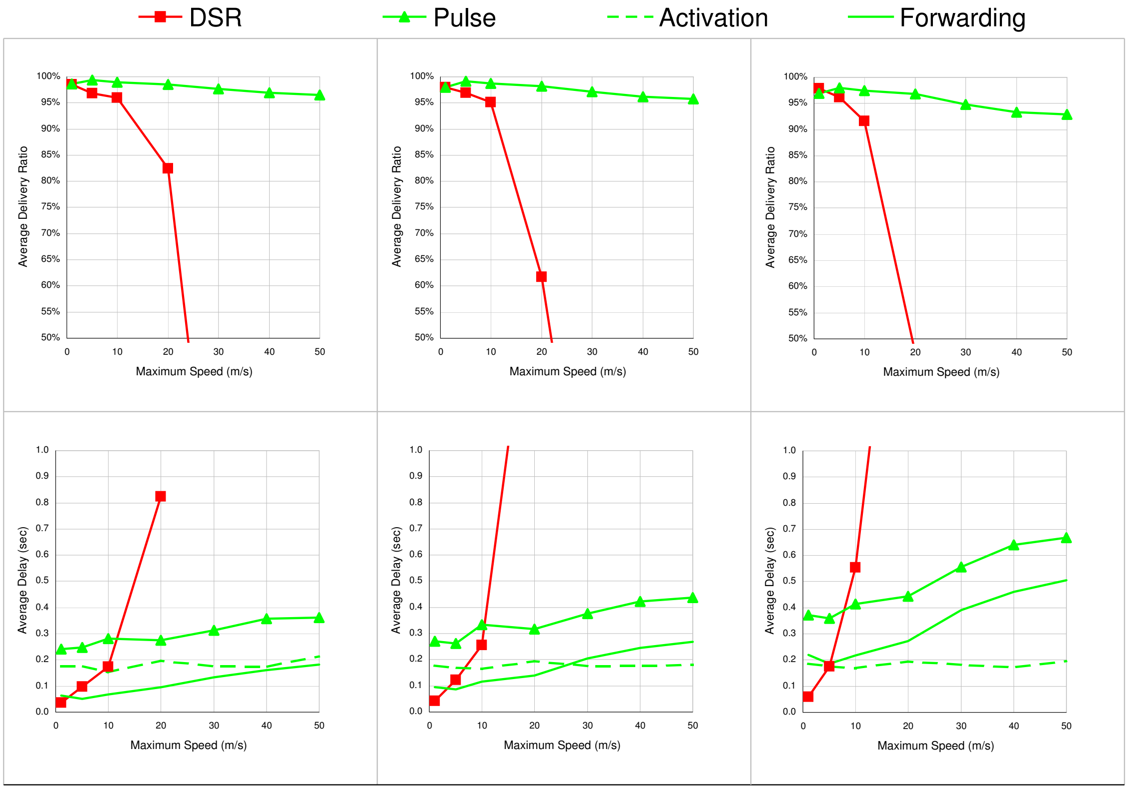
As node density increases the overhead of a flood increases. This affects both the Pulse protocol and DSR. The impact on DSR is greater since it floods more then the Pulse protocol in most cases. The Pulse protocol operates with tight timings for energy efficiency. As a result, when the flood propagation time increases, the amount of time remaining for reservation packets decreases. This results in a reduction in the maximum number of connections which can be simultaneously supported. This is evident in the decrease in the delivery ratio under high load at high node density.

3.4. Delay Evaluation

In order to evaluate the delay characteristics of the routing protocol simulations were performed with 50, 100, 200 nodes in the 5 m/s max speed scenario. The results are indicated in Figure 4. The graphs display the average per packet end-to-end delay of both the Pulse and DSR protocols. In addition, the Pulse protocol's end-to-end delay is broken down into two components. The route activation delay experienced by a packet is the sum of the time spent waiting for the next pulse period at an inactive sending node, and the time spent waiting at the pulse source while the destination is being paged. The network forwarding delay experienced by a packet is the remainder of the end-to-end delay not included in the activation delay, this includes time spent in interface queues as well as being held during the pulse period. The average over all packets of each of these delays is displayed in the figure.

A number of important observations can be made based on the delay results. When using a connection oriented protocol, such as TCP, only the initial connection establishment packet will experience the activation delay, while all the data packets will only experience the network forwarding delay. In addition, the activation delay is predominantly a result of the power saving capabilities of the protocol, so if power saving was not employed, the average per packet end-to-end delay would closely resemble the network forwarding delay. The effects of network density are also evident in the delay results. As the overhead of the flood increases, and the time remaining for reservation packets decreases, activation delay increases as some of the reservation packets fail to reach the pulse source before the end of the pulse period.

Recall that the worst case activation delay when establishing a peer-to-peer connection with the Pulse protocol is



0.15 Mbps

0.20 Mpbs

0.25 Mbps

Figure 5. Mobility scalability in the 1km x 1km - 50 node scenario

two pulse intervals (2 seconds with a one second pulse interval). In practice the activation delay can be lower then the worst case. There are a number of reasons why this is true. The fast activation feature of the protocol enables a large fraction of the network (neighbors of any active path) to avoid the delay incurred by waiting for the next pulse. In addition, paging is unnecessary if the destination node is already active sending, receiving, or forwarding data. If both cases are true, activation delay is completely eliminated.

3.5. Mobility Scalability Evaluation

In the previous simulations the Pulse protocol showed almost no decrease in performance as mobility increased. In order to further evaluate the effects of mobility a number of additional experiments were conducted. In the 50 node case maximum speeds of up to 50 m/s were simulated with loads of 0.15, 0.20 and 0.25 Mbps. The results are displayed in Figure 5 and show that the delivery ratio and delay scale approximately linearly with the maximum speed.

These results indicate that the Pulse protocol is able to perform well under a wide range of node mobility. The Pulse protocol maintains routes to the pulse source proactively, updating them every pulse interval. The proactive route maintenance helps prevent route failures from occurring and fixes them quickly when they do occur. Typically, routing protocols attempt to detect route failures and take action after they occur. For example, if a route failure is detected in an on-demand protocol it might attempt to perform a local repair, or flood the network with a route request. As the node mobility increases, the overhead of on-demand protocols increases since they need to maintain routes which are breaking often. Since the Pulse protocol is pro-actively maintaining routes and not re-acting to route failures, it is able to perform well even at high levels of mobility.

3.6. Density Scalability Evaluation

In order to specifically isolate node density, an additional set of experiments were conducted. Using a 1km by 1km - 5 m/s max scenario with offered loads of 0.10, 0.15, and 0.20, the node density was varied from 50 to 500 nodes per square kilometer. The results are indicated in Figure 6. The main obstacle to scaling in high density networks is operations which require every node to transmit, such as a flood or a hello protocol. It is the increased overhead of flooding which limits DSR's scalability in these scenar-

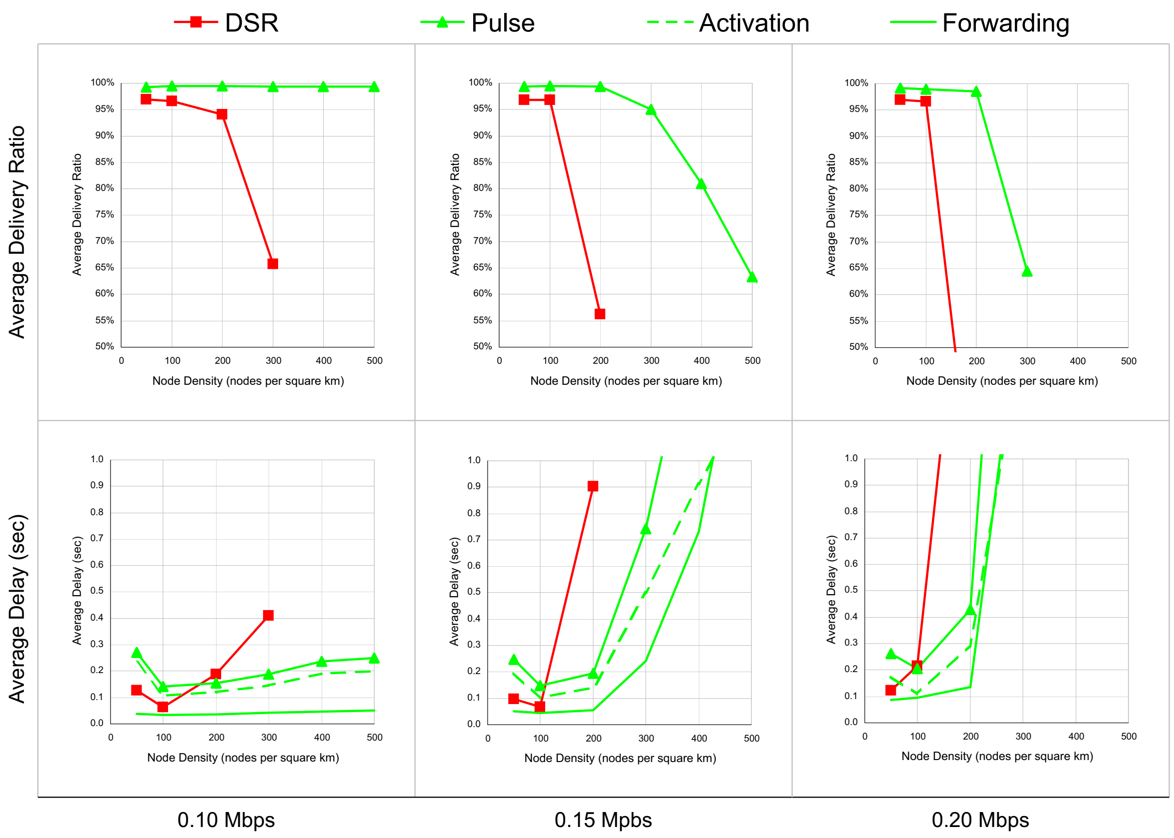


Figure 6. Density scalability in the 1km x 1km - 5 m/s max scenario

ios. In order for the Pulse protocol to function correctly, it needs to be able to operate within its tight timings. This is strictly a requirement of the power saving aspect of the protocol. As the number of nodes increases, the overhead of the pulse flood grows making it more difficult for the protocol to function. In addition, as the offered load increases, the number of reservation packets increases making it even more difficult to meet the timing requirements. If power saving was not required, the pulse flood would consume additional overhead, but the protocol would be able to operate successfully at much higher node densities. If scalability to high node density and energy efficiency are both priorities, the protocol can be tuned by increasing the pulse period at the expense of reduced power savings due to the increased duty cycle.

3.7. Energy Efficiency Evaluation

Figure 7 shows the average per node power consumption versus the average offered load in the 1km x 1km - 100 node - 5 m/s max scenario. The graph is composed of five lines which help visualize the energy consumption results. The *Sleep State line* and *Idle State line* are provided for reference. The Sleep State line indicates the power consumption of a node which never powers on its radio, and represents the lower bound of any power saving protocol. The Idle State line represents the power consumption of a node which has its radio powered on, but neither sends or receives packets. This is the lower bound of any protocol which does not de-active nodes for power saving.

The *DSR line* indicates the average per node power consumption of nodes running the DSR protocol under varying traffic loads. The error bars on this line show the average minimum and maximum power consumption. The average maximum node power consumption is computed by taking the node which consumes the most power from each random scenario, and averaging the power consumptions of these nodes together. The average minimum is computed similarly using the nodes which consume the least amount of power in each random scenario. DSR's power consumption is completely dominated by idle energy consumption. The additional energy used by transmission and reception of packets is less than 10% of the overall consumption in all simulated cases.

The *Pulse line* shows the overall average per node power consumption including the power consumption of the pulse

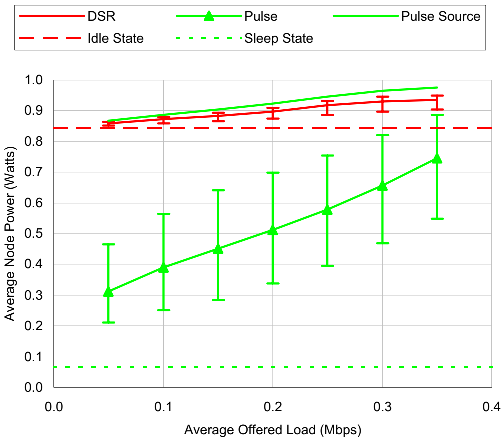


Figure 7. Energy consumption in the 1km x 1km - 100 node - 5 m/s max scenario

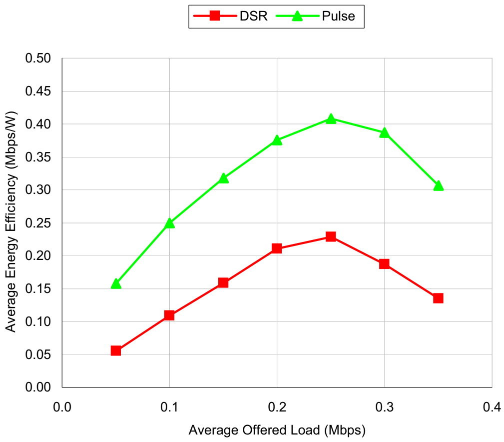


Figure 8. Energy efficiency in the 1km x 1km - 100 node - 5 m/s max case

source. The error bars on this line are computed similarly to the DSR case, except that the pulse source is excluded from the average maximum calculation. Instead the average power consumption of the pulse source is indicated separately on the graph by the *pulse source line*. The average power used by a node running the Pulse protocol is substantially less than that of a node running DSR. We see a savings over the DSR protocol of between 20% and 64% depending on offered load. The strong linear relationship between offered load and energy consumption is a direct result of the path activation feature of the Pulse protocol. This feature causes all nodes that are sending, receiving, or forwarding traffic to enter a full power on state in order to maximize network performance. As a result, the average power usage is directly related to the fraction of nodes that are activated. There is also a direct relationship between the offered load and the number of simultaneously sending nodes when using our exponential on/off traffic generator. As the network load increases, the number of senders increases, which determines the fraction of active nodes in the network. The fraction of active nodes determines the final average power consumption. If the load is increased to the point where every node in the network is transferring packets, the Pulse protocol would use virtually the same amount of power as an on-demand protocol. At the opposite extreme, when there is no load on the network, the power reduction capabilities of the Pulse protocol have the maximum effect.

One interesting aspect of the results is that even though a large fraction of the network traffic may move through the pulse source, its average power consumption is only marginally higher than the average node running DSR (less than a 5% increase). Also, since the Pulse line average includes the contribution of the pulse source, it represents an accurate estimation of the average node power consumption had the pulse source been rotated. While it would not effect the average, rotating the pulse source allows all nodes to fall within the error bars with no node consuming as much power as a node running DSR.

Figure 8 plots energy efficiency (megabits per second per watt of power consumption) versus the offered load. This shows that even though the average power usage increases with higher offered loads, the energy efficiency also increases. In other words, the higher energy consumption rate is offset by the higher throughput rate obtained, increasing the overall efficiency. We see that the efficiency continues to increase until the network reaches saturation. At this point, congestion prevents further throughput increases. Since DSR consumes energy at an almost constant rate regardless of load, the energy efficiency is directly related to the obtained throughput. Thus, a linear increase in efficiency with offered load is observed until the protocol reaches saturation. The Pulse protocol achieves approximately 2 to 3 times the energy efficiency of the DSR protocol in the simulated scenarios.

4. Related Work

There has been a great deal of research conducted with regard to energy efficiency in wireless ad hoc networks as well as in sensor networks where it could be considered even more important due to more limited resources. In general, this work seems to fall into two main categories. The first technique attempts to control the amount of power used to transmit a packet such that only the power required to get the packet to a specific destination is used [15][4][5]. The second category involves the design of distributed protocols which allow the nodes of the network to be placed in a sleep mode. The sleep mode category is further divided into three types of approaches: connected active subset [6] [16], asynchronous wake up [18], and synchronous wake up [19]. The Pulse protocol falls into the synchronized wake-up catagory, but differers from the existing synchronized protocols in that the time scale is much larger, and that a pro-active routing service is provided simultaneously to the power saving functionality. The larger time scale of the Pulse protocol allows it to operate with much courser time synchronization (on the order of 10 milliseconds) which can be implemented without MAC layer integration.

5. Conclusion

We have shown that the Pulse protocol is an effective and energy efficient mobile ad hoc network routing protocol. The Pulse protocol was able achieve high delivery ratios under a wide range of network densities, mobilities, and traffic loads. The results indicate that the protocol is particularly effective when scalability, mobility, and energy efficiency are simultaneously desired.

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