Implementation with Mobile Ad-Hoc Network Routing Protocols

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***Abstract:** This paper outlines our experience with the implementation and deployment of two MANET routing protocols on a five node, four hop, network. The work was prompted by the lack of published results concerning the issues associated with the implementation of MANET routing protocols on actual wireless networks, as opposed to results of simulation experiments. We examined implementations of two distance vector MANET routing protocols and found a number of problems with both protocols during the course of our experiments. The most significant was that neither protocol could provide a stable route over any multi-hop network connection. The route discovery process of both protocols is fooled by the transient availability of network links to nodes that were more than one hop away. Packets transmitted over a fading channel cause the routing protocol to conclude incorrectly that there is a new one hop neighbor that could provide a lower metric (hop count) route to even more distant nodes. This can occur even when nodes are stationary, mobility resulted in even less route stability.*

We implemented a simple signal strength based neighbor selection procedure to test our assertion that fading channels and unreliable network links were the cause of the failure of the routing protocols. The result was that neighbor discovery and the filtering for neighbors with which nodes could communicate reliably enables the creation of reliable multi hop routes. Based on our experiences, we outline several recommendations for future work in MANET research.

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INTRODUCTION

The term ubiquitous computing was coined by Mark Weiser to describe a state of computing in which users are no longer aware of computation being done [28]. The emergence of smart environments, where devices are embedded pervasively in the physical world, has sparked many new research areas and represents a step towards ubiquitous computing. To this end, researchers have begun to outline plans to achieve ubiquitous computing. For example, Basu et al. [3] advocate the vision of power-up-n-play for smart environments in which no predefined infrastructures are installed and, when powered up, the devices "intelligently" configure and connect themselves to other devices. Bhagwat et al. [4] also focus on the interoperability of sensor devices and present three research issues: (1) distributed algorithms for self-organizing devices, (2) packet forwarding, and (3) Internet connectivity.

Mobile ad-hoc network (MANET) routing protocols play a fundamental role in a possible future of ubiquitous devices. Current MANET commercial applications have mainly been for military applications or emergency situations[25]. However, we believe that research into MANET routing protocols will lay the groundwork for future wireless sensor networks and wireless plug-n-play devices. The challenge is for MANET routing protocols to provide a communication platform that is solid, adaptive and dynamic in the face of widely uctuating wireless channel characteristics and node mobility.

The paper discusses our experience while implementing and deploying two distance vector MANET routing protocols. We examined both a public domain implementation of the Ad Hoc On-Demand Distance Vector (AODV) [21] routing protocol and implemented our own version of the Destination-Sequenced Distance Vector (DSDV) [20] routing protocol.

The choice of routing protocols was pragmatically based on what (little) was available at the time this work was carried out. The AODV implementation was the freely available MAD-HOC implementation [15]. This implementation was based on an earlier draft of the AODV protocol and includes some MAD-HOC specific extensions. Where AODV is referred to in this paper we mean the MAD-HOC implementation unless otherwise stated. At the time our work was carried out this was the only public domain MANET routing protocol implementation that had a license suitable for our use and that we could get to compile, run and work on our network. Faced with no other available public domain code and reluctant to base our work solely on one protocol implementation we coded an alternative. DSDV was chosen due to it's relative simplicity and the fact that it is a table based protocol rather than an "on demand" protocol like AODV. Our implementation was based largely on the paper by Perkins et al. [20].

Both protocols were deployed on a five hop, four node test bed based on Linux workstations and 802.11b wireless LAN cards configured to use the Lucent ad hoc mode. We found that neither protocol could provide stable multihop network routes.

The main cause was the failure of the route discovery processes in provisioning for unreliable links which are inherent in wireless channels. The route discovery process was fooled by transient link availability with nodes that were too distant for reliable communication to take place. A couple of routing packets sent over this link is enough to temporarily fool the routing protocol into assuming a more direct (lower hop count) route exists to the desired destination. To test the assertion that transient link availability was the cause of the failure of the routing protocols we developed a signal quality based neighbor selection program called powerwave.

The inclusion of powerwave for neighbor selection stabilized multi-hop routes for both routing protocols to the point where they could carry useful amounts of user data. A number of extensive simulation studies on various MANET routing protocols have been performed by various researchers [25][5][16][8][7]. However, there is a severe lacking in implementation and operational experiences with existing MANET routing protocols. Previous implementation experiences include wireless Internet gateways (WINGS) [11], implementation of ODMRP [2], AODV implementation by Royer et al. [24] and ABR implementation by To hetal. [27]. These studies only highlighted performance issues specific to the protocol being used. By far the most extensive implementation study to date was conducted by Maltz et al. [17] in describing their implementation of DSR.

Unlike previous work, our work reports on the experience of building an operational ad-hoc network that is capable of carrying useful data. We report several interesting observations not reported elsewhere for the use of MANET protocols within pico-cell environments. It is worthwhile noting that this paper's objective is to report on the operational feasibility of existing routing protocols and efforts undertaken to create a reliable ad-hoc network. In many ways this is a step back towards fundamental issues and away from the MANET routing protocol aspects usually examined in simulation studies. Whereas simulation studies commonly report on performance metrics such as throughput, latency and packet loss this paper reports on the fundamental issue of \do MANET routing protocols work". The answer is yes but, in the case of the two distance vector protocols we examined, only if the inherent unreliable and transient nature of wireless network links are taken into account.

This paper is organized as follows. In Section 2 we provide a brief summary of AODV and DSDV. This is followed by implementation details of both these protocols in Section 3. In Section 4 we describe the testbed used for our experiments. Section 5 presents the problems and observations gained from setting up the testbed and running the routing protocols over it. In Section 6, we present the workings of powerwave. Based on our experience with MANET routing protocols, we discuss issues and problems encountered in relation to existing routing protocols and propose some future directions in Section 7. Finally, the conclusions are presented in Section 8.

2. BACKGROUND

In this section we review the workings of the AODV and DSDV MANET routing protocols. Comprehensive reviews of other routing protocols are available in [25],[12] and [5]. AODV is characterised as an on-demand (also called reactive) routing protocol. Routes are created as needed at connection establishment and are maintained for the duration of the communication session. During route discovery a node broadcasts a route request (RREQ) message for a given destination address. Nodes that have a route to the destination respond to the RREQ by sending a route reply (RREP) message to the source and record the route back to the source. Nodes that do not have a route to the destination rebroadcast the RREQ message after recording the return path to the source. In the event of link breakage a route error (RERR) message is sent to the list of nodes (referred to as precursors) that rely on the broken link. Upon receipt of a RERR message, the corresponding route is invalidated and a new RREQ may be initiated by the source to reconstruct the route [21]. The time-to-live (TTL) held is used in RREQs for an expanding ring search to control ooding. Successive RREQs use larger TTLs to increase the search for destination node.

Unlike AODV, DSDV [20] is a table-driven (or proactive) routing protocol and is essentially based on the basic distributed Bellman-Ford routing algorithm [1]. Each node in the network maintains a routing table consisting of the next hop address, routing metric and sequence number for each destination address. To guarantee loop free operation, routing updates from a given node are tagged with a monotonically increasing sequence number to distinguish between stale and new route update messages. Nodes periodically broadcast their routing tables to neighbouring nodes. Given sufficient time, all nodes will converge on common routing tables that list reachability information to each destination in the network. Route updates are generated and broadcast throughout the network when nodes discover broken network links. Nodes that receive a route update check to see if the sequence number specified in the route update message is higher than the sequence number recorded in their own routing table before accepting the update. DSDV reduces routing messages overheads by supporting both full and incremental updates of routing tables.

The main characteristic of table-driven protocols is that a route to every node in the network is always available regardless of whether or not it is needed. This results in substantial signaling overhead and power consumption [25]. Furthermore, table driven protocols transmit route updates regardless of network load, size of routing table, bandwidth and number of nodes in the network [5]. Interested readers are referred to Toh et al. [25] for a qualitative comparison based on simulation experiments between avors of both ondemand and table-driven routing protocols.

3. EXPERIMENTAL OBSERVATIONS

3.1 FADING AND TRANSIENT NETWORK LINKS

It was found that transient radio links resulted in poor operation of both the routing protocols examined where no reliable routes could be established. The poor operation was due to the creation and maintenance of routes without taking the stability, or quality, of the network links comprising the route into account. The fundamental problem was that successful transmission of a datagram over a wireless network link is probabilistic, regardless of lower level protocols. In practice this probabilistic effect became evident in two ways; occasional dropped packets on a normally \good quality" network link and occasional successful packet transmissions on a normally \poor quality" network link. We found that the occasional dropped packet did not present much of a problem for either of the routing protocols examined. On a \good" network link the link layer acknowledgements in 802.11 replaced lost unicast packets and the routing protocols appeared to be able to handle the occasional lost broadcast, or multicast, packet. In contrast the occasional appearance of a channel between two nodes that could not normally communicate was disruptive to the routing protocols on our testbed. The problem manifested itself in the creation of network routes that were not suitable for the reliable transmission (and reception) of user data. These routes were chosen over other route options by the protocols selecting for lowest hop routes, regardless of any sort of measure of route quality. As stated in the introduction a similar effect for the DSR routing protocol has been observed on another testbed [18].

We found that it was practically impossible to establish a stable telnet session between nodes over a three or four hop route on our testbed. For example when using the topology described in Figure 4, we found that Node1 could still detect Node3's signal occasionally despite careful placement and orientation. As a result we observed that both nodes would randomly receive a packet from the other. If AODV was engaged in a route building process it would use the unreliable one hop route from Node1 to Node3 in preference to the two hop alternative. DSDV would replace the existing two hop route between the nodes with the unreliable one hop route. Very little user data would be transmitted over this unreliable route and user sessions would hang pending the reestablishment of the more reliable two hop route.

In a related work, Maltz et al. [17] reported similar behavior while building a MANET testbed and experimenting with Dynamic Source Routing (DSR) routing protocol. The following modifications to DSR were suggested to overcome the problem of routing over unreliable links: (1) monitor route error on links, (2) use the geographic positioning system (GPS) to determine the neighbor proximity (assuming physical proximity will provide the best channel) and (3) combine GPS with route error monitoring. Reliability was tested over a three node, two hop network with the nodes arranged in a line. The network included packet filtering software to prevent packets from being transmitted directly from one end node to the other. They found that an FTP _le transfer between the end nodes was more reliable when the packet filtering software was enabled. Ramanathan et al. [22] also reported problems with transmission range when testing out their quality of service (QoS) based routing protocols.

However, no solutions to unreliable links were suggested. Published articles reporting on MANET routing protocol performance often rely on simulation experiments. Experiments run on our testbed uncovered considerable difference in the probability of successfully receiving packets on a MANET node versus the probability of successful packet reception in some simulation environments. In a simulation environment, such as ns-2 [10], it is generally assumed that the probability of receiving a packet is effectively one (pending collisions etc) and once a node moves out of another node's signal range, or a given distance, this drops to zero. However, our experiments have shown that this is unrealistic; signals tend to decay slowly and there is no cutoff point. We suspect that the use of simplistic radio propagation models in MANET simulation environments has led to inaccurate assessments of the performance of various routing protocols, especially those which utilize hop count as the dominant route selection metric. Thus, one area for future work is the incorporation of better radio propagation models that support channel fading and other inputs to the probabilistic nature of wireless channels. For example, Rappaport [23] lists a number of factors that affect fading in an in-door environment such as multi-path propagation, mobile node speed, surround object speed and signal bandwidth.

3.2 HANDOFF IN A MANET

In conventional cellular networks, the signal-to-noise ratio (SNR) of the connection between mobile phone and base stations is monitored to determine when to hand o_ from one base station to another. In a MANET, current protocols do not predict when a link's SNR will fall below a threshold. The periodic HELLO messages in AODV and route update timers in DSDV are not used to anticipate hand o_, they indicate presence or absence of a neighbor node. Consequently, the route maintenance process at both AODV and DSDV is only initiated after link breakage already ocurred. DSDV behaves differently depending on the mobile nodes direction of movement. DSDV pro-actively changed to a lower hop count route if one was available, but hung on to a route until it is explicitly broken should a lower hop count route not be available. The effect with DSDV was smooth handover when MH2 (in Figure 4) was moving downstream but no handover in the upstream direction.

In the upstream direction two things would prompt a new (higher hop count) route to be used. First, the connection to the previous fixed node would have to timeout prompting a switch to the next best available route being advertised by the new neighbor. Or second, the link between the previous fixed node would have to break along with a route advertisement being received from the new neighbor with a higher hop count and a higher sequence number. The new sequence number would then invalidate the old route and cause the new route to be used instead.

3.3 AODV SPECIFIC ISSUES

3.3.1 PICO CELL SIZE AND AODV'S TIMERS

A problem encountered were AODV's default parameters. Since the transmission range of each node was reduced in our testbed to less than 5m, we had in effect constructed a network with pico sized cells. In this environment the default MAD HOC AODV timers unnecessarily prolonged route construction and required tunning before an acceptable performance could be achieved. The parameters we changed are listed on Table 1. AODV's parameters as specified in [21] are left to the implementors, however recent drafts have used more conservative parameters than those in the MAD-HOC implementation shown in Table 1.

BCAST ID SAVE is used to prevent over ooding of RREQ messages. When a new RREQ is intercepted, the information within the RREQ is recorded and the information is added to an interval queue along with a time interval (current time plus BCAST ID SAVE). In the event of another RREQ appearing within this time interval, the RREQ is discarded. RREQ RETRIES bounds the number of RREQs for a given destination. The default value is two. We found this value to be too conservative, and found that five was more appropriate value.

ACTIVE ROUTE TIMEOUT is used to determine the lifetime of a given route. The lifetime of each route maintained by a given node is refreshed after observing data packets or HELLO messages on that route. In a pico-cell environment, the default value needs to be small. In our testbed where nodes moved at slow walking pace, the time for a node to traverse given cell was around five and we found a route timeout value of one second was appropriate.

Both NODE TRAVERSAL TIME and NET DIAMETER had to be modified to suit our network topology. The NODE TRAVERSAL TIME was modified to increase the route construction time. The default value of NET DIAMETER was set to 35 nodes and this was changed to five to reect the number of nodes in our test bed.

The last parameter to be modified was ALLOWED HELLO LOSS which determines how many HELLO messages are lost before a link is considered broken. Routes were timing out frequently in our testbed and we set the ALLOWED HELLO LOSS parameter to five to increase stability. The optimization of AODV by changing the parameters to suit our testbed was done on a trial and error basis. To date there are no published guidelines or heuristics for setting AODV's parameters or adapting them to a given network.

The parameters shown in Table 1, and the other AODV parameters that have been defined in the AODV specification [21], would most likely have to be modified for use in other networks.

3.3.2 ARP INTERACTIONS

The reliance of the MAD-HOC AODV implementation on sniffing ARP packets to signal the need for route construction led to two problems. The first problem was that packets were not buffered while the route was being built. As mentioned in Section 3 this led to packets being dropped and the need to start an application such as telnet a number of times before a route was actually built. The second problem was that a route will never be constructed if there is an entry in the ARP cache. Spurious ARP cache entries exist for one or more reasons. Either the two nodes in question had once been adjacent, and the ARP cache entry had yet to time out, or an ARP reply was un-expectedly received from a remote node (over an unreliable link) and the cache then prevented a more reliable route being found. One work around to these problems was to regularly push the ARP cache and to start applications multiple times while waiting for the route building process to complete. In practice this would be achievable by using ping and waiting for a successful reply before starting the intended application.

A better solution is the one proposed in [24] that uses a netlink socket to communicate routing information with the kernel space and a dummy route for buffering data packets pending route construction.

3.4 DSDV

3.4.1 ROUTE STABILITY

The first thing we noticed about our DSDV implementation was its relative stability compared to the MAD-HOC's AODV implementation. DSDV was less affected by unreliable connections to distant nodes. This was mainly due to the use of the SEEN metric (requiring a handshake before the link would be used in routes) and less interaction with the ARP cache as the routing table was pre-populated with host routes (negating the need to ARP).

However DSDV was adversely affected by transient link availability. Even when all the network nodes were stationary the routing table would slowly "churn" as routes were constructed to distant nodes and then timeout.

4. DISCUSSIONS AND FUTURE WORK

4.1 UNSTABLE LINKS

The majority of MANET routing protocols described in the literature were designed to handle topology changes and do not take unreliable links into account. Currently, only signal stability based adaptive routing (SSA) [9], ABR [26], and longest life routing protocol (LLRP)[29] support the notion of reliable routes. The route metrics use by SSA are average signal strength and route stability. By using these route metrics, packets will always be routed through the most reliable route (possibly closest node). Thereby route reconstruction cost is reduced and reliability of established route increases [9].

Unlike SSA, ABR only use route stability as the routing metric. Route stability is defined as the number of HELLO messages observe from a given neighbor. Hence, a neighbor with a given HELLO message count is considered stable. In both SSA and ABR, the destination has to choose the best route to take from a number of alternatives recorded from the various route requests received [29]. Further, once a route is setup there are no considerations for degraded links along the route. Routes are only rebuilt once they are broken. The immediate future work is to re-evaluate existing hop based routing protocols with the addition of unreliable links.

4.2 SMOOTH HANDOFF

The notion of smooth handoff in MANET routing protocols has generally been overlooked. Improvements may be made by intelligently monitoring surrounding neighbors and determining whether a given node is able to prime an upstream/downstream node with a route to the destination. We found that a relatively smooth handover could be achieved by generating regular RREQs from MH2. In other words, when a node detects a new neighbor a special message could be sent to prime the new neighbor, with routes to other new receiver nodes without waiting for existing routes to break. Pro-active route construction will cause unnecessary traffic and duplicate routes which may then lead to the difficulty of removing invalidated routes. Further, the problem becomes more complicated if mobility is taken into account. Unlike traditional one hop wireless networks (e.g., cellular) where base-stations are fixed, the handoff decisions in MANETs are much more complicated.

It is interesting to note that the powerwave neighbor selection process had the side-effect of enabling a degree of handoff. The neighbor selection process filtered out neighbors before the network link disappeared entirely. User datagrams could still be forwarded over the link while the routing policy engine was finding a new route. It worked in our implementations because the routing parameters and the rate at which MH2 moved matched.

4.3 TOPOLOGY DEPENDENT PARAMETERS

Our experiments showed that the protocol parameters in both MAD-HOC's AODV and DSDV required some tuning before they would work properly. The determination of suitable timer values depended on channel rates, network topologies and mobility patterns [8]. The impact of these parameters on the performance of upper layer protocols is left for future work.

One method to allow for adaptive parameters is to introduce additional information. Protocols may rely on GPS, for example location aided routing protocols, to gather more information such as network topology and nodes proximity. Once the range of adjacent nodes are estimated, parameters may be adjusted accordingly.

4.4 NEIGHBOR SELECTION SUB-LAYER

The Internet MANET encapsulation protocol (IMEP) [6] is a mechanism to aggregate and encapsulate control messages. Also, IMEP provides a generic multi-purpose layer containing various common functionalities for MANET routing protocols. However, in the IMEP specification no consideration for signal strength was presented. It may be possible to use IMEP for filtering neighbors based on link stability rather than just to list neighbors that are in range.

Given the observations obtained from our experiments, one possible area of work is to extend upon IMEP's functionalities to incorporate mechanisms to shield wireless defects, and also over various routing metrics which could be used by routing protocols.

5. CONCLUSION

In this paper we have outlined our implementation and deployment experiences with MAD-HOC's AODV and DSDV. Our experiments have provided insights into the real world deployment of MANETs and highlight issues that require further investigation. These are:

1. Handling unreliable/Unstable links.
2. Minimizing the dependacy on topology specific parameters.
3. Mechanisms for handoff and reducing packet loss during handoff.
4. Incorporating neighbor discovery and filtering into a neighbor selection sub-layer.

The first issue is a result of the current prevailing MANET protocol development/testing environments which appear to consist almost entirely of simulation experiments using ns- 2 and Glomosim. In implementing two MANET routing protocols, rather than simulating them, we discovered that the variability of networking conditions in the radio environment was such that the routing protocols did not work as reported in the literature. This led to the development of powerwave, and it was found that neighbor selection is crucial in the operation of MANET routing protocols. We believe our observations pertaining to unreliable/unstable links are not restricted to MAD-HOC's AODV implementation given that current AODV speci_cation relies on hop count and does not take into account the reliability of a given route or link.

The second issue is specific to a given routing protocol. As argued, having pre-configured parameters for a given topology is inappropriate given the inherent dynamic nature of MANETs, and affects the operation of routing protocols. Therefore, methods for adaptive adjustment of these parameters are required.

On the third issue, current MANET routing protocols do not appear to consider pre-emptive route construction based on signal strength in a similar way to how handoffs are done in cellular networks. We have observed that knowing whether a node is going upstream or downstream has added benefit. The concept of handoff, from one route that has a high probability of near term breakage to another route which is more stable is a possible area for future research.

Finally, there is scope for the development of a neighbor selection sub-layer like IMEP that incorporates a range of metrics that could be used by routing protocols. Various filters and heuristics could be developed which will be beneficial to MANET routing protocols.

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