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Robust and flexible Internet connectivity for mobile ad hoc networks

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ABSTRACT

An important challenge for the wider adoption of mobile ad hoc network (MANET) technologies is finding ways to efficiently interconnect them with the Internet. However, such interconnections prove difficult due to differences in mobility, addressing and routing between MANETs and existing IP networks.

In this paper, we review the existing solutions to interconnect MANETs with the Internet, but find them lacking in robustness and flexibility. For instance, many solutions do not consider the presence of multiple gateways, and in such scenarios they either fail, or are less efficient due to the lack of multi-homing capabilities.

A key insight of ours is that the reason for routing failure is usually an interconnection scheme's inability to express *indirection* (i.e., a way to enforce routing through a certain gateway on the path toward a destination in the Internet). Another problem concerns *state replication* where a route update fails to replicate all the routing state needed to forward packets to an Internet gateway.

We analyze the above problems and suggest a solution that provides robust and flexible Internet connectivity. With minor adaptions our solution works for any MANET routing protocol, and has support for multiple gateways and multi-homing. Simulations show that, when used in combination with AODV routing, our solution provides up to 20% delivery ratio improvement over one of the main alternatives. A prototype implementation illustrates the feasibility of our solution in the real world.

1. Introduction

In recent years, routing protocol implementations for mobile ad hoc networks (MANETs) have become increasingly abundant, but practical real world experiences with them are still scarce. One important reason for this, we argue, is that MANET routing protocols are being developed without explicit consideration for Internet connectivity. Interconnecting MANETs with the Internet is an appealing way to extend the reach of wireless base stations, and hence increase the use of multi-hop ad hoc routing. On the other hand, as MANET research is already broad – including scenarios with varying mobility, node capabilities, and routing strategies – it is perhaps not surprising that Internet connectivity is being developed as an add-on to routing protocols in order to limit the scope of the design space.

However, retrofitting Internet connectivity onto routing protocols also opens up for clunky designs due to the risk of building in incompatibilities between MANETs and existing networks. The many variations of MANETs imply that connecting them to the Internet is not as simple as connecting two regular IP networks. For instance, addressing in MANETs is often flat instead of hierarchical and routing protocols may be either reactive or proactive – or a combination of both. Moreover, the traditional concept of an Internet *default route* does not apply to many MANET scenarios, because the usage of a default route is normally determined by the *lack of* explicit routing state, rather than

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the existence of it. Reactive routing protocols, such as AODV and DSR, are designed to maintain only the routing state explicitly used at any time, and are therefore at odds with the default route concept. These protocols cannot easily determine when to use a default route to the Internet over requesting a new route to a node in the MANET.

Apart from routing incompatibilities between MANETs and the Internet, there are challenges related to the lack of network planning. Any node with direct access to the Internet can offer this connectivity to other nodes in the network at will. Hence, there is no control over when and where connectivity opportunities appear, and disappear. The presence of multiple nodes acting as gateways may lead to diverging views on which one to use in order to reach the Internet. Hence, there may be conflicts among nodes in selecting a (default) gateway along the length of a specific route.

It is clear from the above description that the variations in MANETs and their incompatibilities with traditional IP networks pose considerable challenges to interfacing them with the Internet. We categorize the main challenges into four important areas:

- **Addressing:** MANETs are usually IP based, but tend to bend the rules of subnetting and prefix coherency. Within MANETs, addressing is often flat, i.e., the IP address is reduced to an identifier.
- **Routing:** It is more challenging to integrate Internet connectivity with reactive routing protocols than proactive ones, because the former do not maintain complete routing state of the entire MANET, like the latter do.
- **Gateways:** MANETs are normally without administrative authorities, and any node can potentially offer connectivity to the Internet. Therefore, multiple gateways may be present at the same time.
- **Mobility:** Mobile nodes may move within a MANET, as well as between different MANETs. An Internet connectivity scheme should therefore seamlessly integrate with global connectivity solutions, such as Mobile IP, in a way that is natural for the routing protocol used.

In this paper, we argue that a solution for MANET Internet connectivity must be *robust* enough to cope with the challenges in each of the above areas, and *flexible* enough to exploit opportunities to improve performance or reliability, e.g., by doing multi-homing or load-balancing. In the rest of the paper, the above areas of challenge will be the outset from were we analyze existing Internet connectivity schemes and from were we construct and evaluate our own one. We further discuss the impact of these challenge areas on the design of MANET Internet connectivity when we diagnose the problem in detail in Section 2.

Questions that follow from the above challenge areas are how existing Internet connectivity schemes cope with them, and how robust and flexible the schemes are? When surveying the existing proposals for Internet connectivity, we found them lacking in how they handle one or more of the above challenges. For example, one of the most prominent proposals [17] (which has been proposed for standardization) adopts the default route approach without clearly addressing the issues of flat addressing and multiple gateways. Other schemes may not have the problems related to default routes [11,6], but they either do not consider macro mobility, are designed specifically for the less challenging proactive routing, or do not suggest how to handle multi-homing or load-balancing. Moreover, most solutions target specific routing protocols without discussing how they fit with alternative routing schemes. And, unfortunately, most proposals furthermore lack implementations and proper evaluations. We further discuss alternative solutions in Section 6, where we describe related work.

One of the key contributions we make to address the challenges of Internet connectivity follows from our problem diagnosis and survey of existing protocols; namely the insight that Internet connectivity schemes must support *indirection*. Indirection allows the routing of Internet traffic to a specific gateway that may not be the “closest” one. Under mobility, such indirect routing is required to maintain flows to old gateways while the flows are bound to state in them. The lack of indirection in many existing proposals for Internet connectivity leads us to believe that the problem of Interfacing MANETs with the Internet has not been properly analyzed, although there may be point solutions that work for specific environments. A goal with this work is therefore to make clear the requirements of MANET Internet connectivity, such as indirection, in order to reduce misconceptions about how to design it, and to minimize the risk of point solutions that only apply to very specific scenarios and protocols. The hope is that our work can aid designers in making, in our view, the right decisions that lead to robust and flexible Internet connectivity for MANETs.

An example consequence of excluding indirection in the design is, what we call, the *state replication* problem. Its discovery is another one of our contributions. State replication is mainly a problem in reactive hop-by-hop protocols, such as AODV, and manifests itself when a route to an Internet gateway is changed by an intermediate node due to route optimizations or repairs, without all nodes along the route being notified. Any new nodes that become a part of the updated route must not only have the routing state required to reach the gateway, but also some state for the Internet destination in order to, e.g., avoid subsequent route discoveries when forwarding data packets destined for the Internet. Further, if the route is updated, such that it leads to a new gateway, the sources of any flows along the route may need notification to re-register with the new gateway,[1] because their return traffic may otherwise be lost at the old gateway (see Section 3.3.3 for a detailed description of this problem and its consequences).

Indirection is not a new invention in MANET routing. Indeed, some protocols, such as DSR, have built in indirection support (in DSR’s case due to its source routing nature). Other protocols, such as AODV, may need to be complemented with additional indirection mechanisms, such as tunneling [11]. In previous work [13], we first explored indirection as a requirement for robust and flexible Internet connectivity, and suggested its utility for multi-homing

[1] We assume that gateways maintains state such as NAT tables or Mobile IP registrations.