IP Links in Multihop Ad Hoc Wireless Networks?

Emmanuel Baccelli
E-mail: Emmanuel.Baccelli@inria.fr
INRIA Saclay, France
Thomas Clausen, Ulrich Herberg
Ecole Polytechnique, France
Charles Perkins
Wichorus

Abstract

A number of efforts currently aim at scalable and efficient mobile ad hoc routing, an essential piece concerning the integration of such networks in the Internet. However, there is another independent and important issue, namely, how can existing Internet networks and ad hoc networks co-exist coherently within the same protocol architecture. A fundamental concept in the IP protocol suite is that of a link. The link concept has so far been key to the scalability of IP networking. This paper identifies and discusses issues regarding the formalisation of a similar concept in the multi-hop ad hoc networking context – one of the first steps that must be taken in the near future, in order to be able to accomodate ad hoc networks in the Internet.

1. Introduction

A multi-hop ad hoc wireless network is a collection of devices that have wireless transceivers and that provide store-and-forward functionalities on top of the physical and medium access protocols in use, as needed to enable multi-hop wireless communications (see Fig. 1). Such devices can thus be classified as routers in the resulting wireless network, which is also known as a MANET. In this realm, the devices can be referred to as MANET routers, which have at least one MANET interface – for instance in Fig. 1, the MANET interfaces are the radio interfaces. In the following, we will assume for simplicity that the MANET interfaces all use the same physical and medium access protocol, even though this is not necessarily the case.

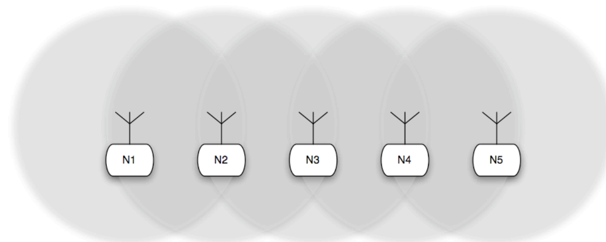

Figure 1. MANET communication. The light grey area indicates the radio coverage area of each MANET interface. Store-and-forward functionalities are provided to achieve multi-hop radio communication, for instance between N1 to N5, which cannot communicate directly since they are out of radio range from each another.

1.1. MANET Scenarios

Two types of MANET scenarios can be distinguished. In the *subordinate MANET scenario* the MANET is connected to at least one external network (typically the Internet) that requires a configured range of addresses on the MANET, i.e. the use of addresses or prefixes derived from a global prefix. Typical instances of this scenario include public wireless networks of scattered fixed WLAN Access Points participating in a MANET of mobile users, and acting as border routers. Another example is coverage extension of a fixed wide-area wireless network, where one or more mobile routers in the MANET are connected to the Internet through technologies such as UMTS or WiMAX.

On the other hand, in the so-called *standalone MANETs* scenario the MANET does not contain any router which imposes the use of such addresses or prefixes derived from a global prefix. Typical instances of this scenario include private or temporary networks, set-up in areas where outside network infrastructure exist (e.g. emergency networks for disaster recovery, or conference-room networks).

From a qualitative point of view, ad hoc networking capabilities substantially increase the survivability of a network in face of infrastructure damage, and provide cheap coverage extension for existing infrastructure. They also provide users with novel private networking opportunities.

1.2. MANETs and IP Interface Configuration

In multi-hop networks, a routing protocol is needed to provide store-and-forward data packets across the ad hoc network. Such protocols are called MANET routing protocols, such as [6] [5]. However, a pre-requisite to the correct operation of routing protocols, is the correct configuration of MANET interfaces. In an IP environment, which is the focus of this paper, this means an appropriate IP address and IP subnet prefix configured on network interfaces.

The IP interfaces of a router are usually configured by a human operator, taking into account the planned layer 3 (L3) topology, i.e. the topology of links connecting this router to other routers and hosts. A traditional example of link is an ethernet wire, which connects a collection of routers or hosts together. The operator would then assign a particular IP prefix to this wire, and then configure an interface to this wire with an IP address matching this prefix and that is not already used, as well as a subnet prefix equal to the IP prefix assigned to this link.

On MANET interfaces however, since MANET routers are likely to be mobile, there is no planned L3 topology. Moreover, a significant fraction of ad hoc nodes may be operated by non-experts (for instance in an emergency scenario). Such considerations suggest that MANET interface configuration should happen automatically, without need for operator intervention. There are currently no such standard solutions for router IP interface autoconfiguration, even though host autoconfiguration solutions like DHCP [4] or SLAAC [1] could be used for this task to some extent, if the MANET is contained within a single hop or link, or if a DHCP server is somehow reachable.

This represents a fundamental issue with respect to MANET inclusion in the Internet architecture. Indeed, most MANETs are not contained within a single hop (one such example is shown in Fig. 1), and in these cases, an important and open question is: as far as IP is concerned, what is a link in a multi-hop ad hoc wireless network? This paper investigates that question. We will first recall the conceptual importance of links in the Internet architecture, and then outline some key characteristics of multi-hop ad hoc wireless communication. We will then conclude with a discussion on the different possible applications of the IP link concept in multi-hop ad hoc wireless environments.

2. Links: Atomic Internet Elements

The Internet became scalable the day local networks suddenly became subnetworks of a bigger entity over which spanned a generic communication standard: the IP suite of protocols. While the Internet could nowadays be abstracted as a single gigantic network, it is still an interconnection of smaller networks. The atomic entity, as far as IP is concerned, is a link connecting two or more network interfaces (on hosts or routers). The archetype link example is an ethernet link: basically a cable connecting several nodes together (see Fig. 2). The simplest example of link is a point-to-point link, which can be seen as a special case of ethernet link, i.e. a cable connecting exactly two nodes. Another common example is a WiFi link connecting user terminals and an Access Point wirelessly (in infrastructure mode), basically also emulating a simple ethernet link.

A network interface connects a node to at most one link, which enables direct communication at layer 3 – in other words IP datagram forwarding is not required, and TTL remains unchanged, for packets delivered to other nodes having an interface on this link. As far as layers 3 and higher are concerned, a link is a bounded layer 2 segment [1], to which a node's network interface may attach. For example, the bounds of an Ethernet link are the bounds of the cable it is made of, and the bounds of a WiFi link are determined by the radio range of the Access Point. Thus, conceptually, a segregation appears between (i) the batch of nodes which have an interface to this link, which are said to be on-link, versus (ii) other nodes, that are said to be off-link. In particular, a node's interface that detaches from a link will immediately notify the node it is now off-link, while other nodes that remain on-link will likely also be quickly notified about that node's departure.

Such segregation allows a straightforward association between a given range of IP addresses (i.e. the IP subnet p:: in Fig. 2), and a link, thus blending name and location into a single identifier: the IP address. An interface attached to this link may be configured with the latter's associated subnet prefix and may be assigned an IP address that matches this prefix. Conversely, an interface that is not attached to this link must not be configured with this subnet prefix or assigned an IP address that matches this prefix. This strict policy is at the base of today's IP architecture, and was one of the key elements that have allowed the Internet to scale to its current size, which was not really foreseen by most of the early pioneers. Indeed the prefix summarization deriving from this policy is the main reason why hierarchical IP routing is so successful, and why routing table growth has been sustainable, being logarithmic instead of linear with respect to the number of destinations in the network.

1. Virtual links (emulations of a link) are not considered here, since they are a further refinement.

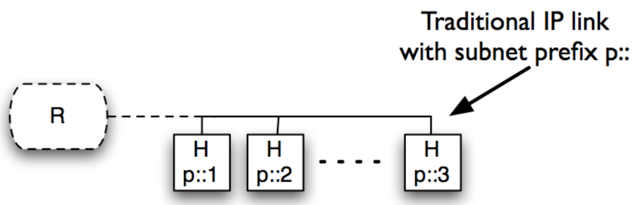

Figure 2. An ethernet link: a cable connecting a router (marked R) and hosts (marked H). The IP prefix p:: is assigned to the link.

3. Multi-Hop Ad Hoc Wireless Characteristics

Let A and B be two nodes in a multi-hop ad hoc wireless network N. Suppose that, when node A transmits a packet through its interface on network N, that packet is detectable by node B without requiring storage and/or forwarding by any other node. In this circumstance, we will say that B can receive packets directly from A. Alternatively, we may also say that B "hears" packets from A. Note that therefore, when B can hear IP packets from A, the TTL of the IP packet heard by B will be precisely the same as it was when A transmitted that packet.

Let S be the set of nodes that can hear packets transmitted by node A through its interface on network N. We will now describe some fundamental characteristics of multi-hop ad hoc wireless communication. Because of these characteristics, some assumptions about packet transmission that are typically made in wired networks, are often untrue in multi-hop ad hoc wireless networks.

3.1. Asymmetry, Time-Variation, Non-Transitivity

First, there is no guarantee that a node C within S can also send IP packets directly to node A. In other words, even though C can "hear" packets from node A (since it is a member of set S), there is no guarantee that A can "hear" packets from node C. Thus, communications may be "asymmetric", often due to variability of the wireless medium.

Second, there is no guarantee that, as a set, S is at all stable. The membership of set S may in fact change at any rate, any time. Thus, communications may be "time-variant", generally due to variability of the wireless medium, or due to node mobility.

Now, conversely, let V be the set of nodes from which A can directly receive packets – in other words, A can "hear" packets from any node in set V. Suppose that node A is communicating at time t_0 through its interface on network N. As a consequence of time variation and asymmetry, we observe that A:

1) cannot assume that $S = V$,
2) cannot assume that S and/or V are unchanged at time $t_1 > t_0$.

Furthermore, transitivity is not guaranteed over multi-hop ad hoc wireless networks. Assume that, through their respective interfaces within network N:

1) node B and node A can hear each other (i.e. node B is a member of sets S and V), and,
2) node A and node C can also hear each other (i.e. node C is a also a member of sets S and V).

This neither implies that node B can hear node C, nor that node C can hear node B (through their interface on network N). Such non-transitivity is often observed on multi-hop ad hoc wireless networks.

3.2. Radio Range and Wireless Irregularities

In Section 3.1 we presented an abstract description of essential multi-hop ad hoc wireless communication characteristics. This section points out a practical reality, at the root of these characteristics. Wireless communication links are often subject to significant limitations to the distance across which they may be established. In the extreme cases, some radio links are measured in centimeters, not meters, although such short-range radio links are not typically considered to support multi-hop ad hoc networks. More often, radio links are encountered with range limited to several tens or hundreds of meters.

The range-limitation factor creates specific problems, observed in multi-hop ad hoc wireless networks. In this context, it is indeed not rare that the radio ranges of several nodes partially overlap. This partial overlap often causes communication on multi-hop ad hoc wireless networks to be non-transitive and/or asymmetric, as described in Section 3.1.

A typical example is the "hidden node" problem, which occurs in Fig. 1. Though the nodes are shown as all having equal communication ranges, they are not at all equally accessible to each other. For instance, nodes $N1$ and $N3$ cannot hear each other. On the other hand, nodes $N2$ and $N1$ can hear each other while $N2$ and $N3$ can also hear each other. When nodes $N1$ and $N3$ try to communicate with node $N2$ at the same time, their radio signals collide. Node $N2$ may only be able to detect noisy interference, and may even be unable to determine the source of the issue. Such problems stem from the non-transitivity of multi-hop ad hoc wireless communications mentioned in Section 3.1, and require specific mechanisms in order to avoid them. These mechanisms generally operate at the link layer, but depending on the exact situation and the link layer technology in use, such problems, and others caused by range-limitation and partial overlap, may affect the IP layer.

Besides radio range limitations, wireless communications are affected by irregularities in the shape of the geographical area over which nodes may effectively communicate [8]. For example, even within radio range, omnidirectional wireless transmission area is generally far from isotropic (circular). Nodes seldom hear each other perfectly, and signal strength often varies significantly. The variation is not a simple function of distance, but rather a complex function of the environment including obstacles, weather conditions, interferences as well as other factors that change over time. The exact analytical formulation of the functional variation is often considered intractable. These irregularities also cause communications on multi-hop ad hoc wireless networks to be non-transitive, asymmetric, or time-varying, as described in Section 3.1 and also require specific mechanisms in order to avoid them.

The mechanisms aiming to avoid problems due to radio range limitation or wireless irregularities generally operate at the link layer. However, depending on the exact situation and the link layer technology in use, such problems, among others, may still affect the IP layer, as described in the following.

4. Links in Multi-Hop Ad Hoc Networks

When it comes to defining what a link is in a multi-hop wireless network, the first task is to identify which link model may be appropriate. As far as the IP suite of protocols is concerned, which is our focus in this paper, the two basic link models that are used [2] are the following:

- the multi-access link model, whereby multiple nodes may be on-link, including zero or more routers. Two nodes on the link are able to communicate without any IPv4 TTL or IPv6 Hop Limit decrement,
- the point-to-point link model, whereby exactly two nodes are on-link, and are able to communicate without any IPv4 TTL or IPv6 Hop Limit decrement,

For instance, the ethernet link is the archetype example of multi-access link. While there are variations around these two basic models, such as NBMA or Point-to-Multipoint, these variations are preferably avoided as they are problematic to handle for many protocols and applications at layer 3 and higher [2]. Identifying a link model for a given layer 2 technology is important for a number of upper layer protocols and applications that switch to different modes of operation, corresponding to the link model.

4.1. Issues with MANET Link Modelling

The multi-access link model, with its built-in broadcast ability, seems at first sight very appealing to model MANET links. However, it is not a satisfactory model for at least two reasons. For starters, as seen in Section 3.1, communication on a MANET link is non-transitive, whereas the multi-access link model stipulates transitive communication over the link, as any two nodes on the link must be able to communicate without IPv4 TTL or IPv6 Hop Limit decrement. Moreover, contrary to any example of multi-access link to date, there are no discrete off-link, or on-link events on an interface to a MANET link.

The point-to-point link model is not satisfactory either for two main reasons. The first reason is that a node often connects to several neighbors at the same time over a MANET interface. In this case, with a point-to-point model, the MANET interface would not attach to a single link as it should, but to several links at the same time (one per neighbor), a situation that is not desireable in the current IP architecture [9]. Furthermore, the point-to-point link model denies the natural broadcast capabilities available through a MANET interface: a single transmission generally reaches several neighbors at the same time. If because of the model, superfluous transmissions must occur, it would be a substantial waste of precious wireless bandwidth.

In fact, MANET links do not fit any existing model. The current Internet architecture is designed to work on networks modeled as mostly static graphs (if needed via the introduction of virtual vertices and/or virtual links), hierarchically organized in a tree-like fashion. MANET topologies, however, are better captured as mostly dynamic *hyper-graphs* as shown in Fig. 3. In a MANET context, the concept of link is difficult to grasp: a pair of neighbors over a MANET ”link” generally hear a different set of other nodes through their respective interface to this ”link”. Thus the impact of a transmission on a MANET ”link” depends on which node transmits – a characteristic not captured by the above-mentioned models. Moreover, the equal roles of the different network elements in a MANET make it most of the time difficult to organize in a meaningful hierarchical structure.

Finally, router topology appears and evolves spontaneously in MANETs. It is not planned in advance by human

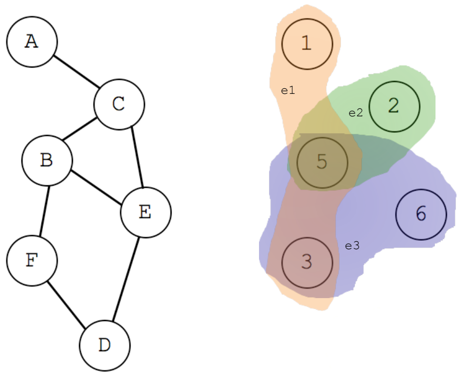

Figure 3. On the left, a graph: each edge connects exactly two vertices. On the right a hyper-graph: an edge may connect more than two vertices, here three edges e1 (gathering vertices 1,5,3), e2 (gathering vertices 5,2) and e3 (gathering vertices 6,5,3).

operators, the way it is usually done in other networks. The very concept of IP link modelling and subnet prefix association reflects this planning in advance of layer 3 topology. Absent such planning, and with the potentially very dynamic topology changes that are often observed in an ad hoc network, it is even more difficult to grasp how a MANET link could be properly defined.

There are several ways that are currently explored in order to cope with the MANET link issue. One approach that was proposed is pushing the issue down to layer 2 (see for instance [7]), where "dynamic routing" would be performed in order to emulate a multi-access link model for layers 3 and higher. However, doing so would exclude heterogeneous layer 2 technologies within the network – a core Internet feature. At large scale, the benefit of this approach is moreover not straightforward to evaluate. Layer 2 networks so far are strictly scoped in terms of space and membership, for good reason. With this approach, however, a layer 2 network could potentially spread without limits, a situation that would need much deeper examination before being advocated.

Another approach is to simply avoid using any link abstraction on ad hoc networks. However, the resulting complexity explosion, due to partial or total IP prefix deaggregation, is to be addressed if large ad hoc networks are targeted. Suppression of link abstractions deprives the Internet from its only means to identify distinct subsets of nodes that can be dealt with as a batch, thus enabling the scalability of protocols that discover and maintain the network. However, in MANETs, where any node may move and neither the set of nodes in the MANET nor their connections to each other is pre-determined, a situation occurs: finding a practical and scalable algorithm for the establishment of such dynamic partitioning, that could be generically used to change the "granularity" of the network, is still an open problem.

5. Conclusion

Solutions are needed to co-organize at large scale, the current Internet on one hand, and on the other hand a growing part of its topology becoming increasingly mobile and dynamic, soon including multi-hop ad hoc networks. The real issues that pertain to this task tackle on one hand scalability, in terms of dynamism and size of the managed topology, and on the other hand legacy, since for obvious reasons, it is not realistic to advocate changes that would require alteration of any protocol already massively deployed in the Internet – a clean-slate approach is thus not realistic in our opinion. Towards the goal of smoothly integrating MANETs into the Internet, this paper identifies and analyzes a key problem: the modelling of IP links in multi-hop ad hoc networks. While the concept of a link has been fundamental to Internet scalability until now, this paper has explained why the legitimacy of this concept is seriously problematic in multi-hop ad hoc networks. These issues must be answered in order to retain a coherent Internet architecture in the near future when ad hoc networks will fully come into play.

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