Use 'em or lose 'em: On unidirectional links in reactive routing protocols

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In reactive unicast routing protocols, Route Discovery aims to include only bidirectional links in discovered routing paths. This is typically accomplished by having routers maintain a “blacklist” of links recently confirmed (through Route Reply processing) to be unidirectional – which is then used for excluding subsequent Route Discovery control messages received over these links from being processed and forwarded.

This paper first presents an analytical model, which allows to study the impact of unidirectional links being present in a network, on the performance of reactive routing protocols. Next, this paper identifies that despite the use of a “blacklist”, the Route Discovery process may result in discovery of false forward routes, i.e., routes containing unidirectional links – and proposes a counter-measure denoted Forward Bidirectionality Check. This paper further proposes a Loop Exploration mechanism, allowing to properly include unidirectional links in a discovered routing topology – with the goal of providing bidirectional connectivity even in absence of bidirectional paths in the network.

Finally, each of these proposed mechanisms are subjected to extensive network simulations in static scenarios. When the fraction of unidirectional links is moderate (15–50%), simulations find Forward Bidirectionality Check to significantly increase the probability that bidirectional routing paths can be discovered by a reactive routing protocol, while incurring only an insignificant additional overhead. Further, in networks with a significant fraction of unidirectional links (≥50%), simulations reveal that Loop Exploration preserves the ability of a reactive routing protocol to establish bidirectional communication (possibly through non-bidirectional paths), but at the expense of a substantial additional overhead.

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1. Introduction

Routing protocols for ad hoc networks can be classified into two main categories: proactive and reactive. Proactive protocols use a periodic routing control message exchange to build routes to all destinations, before, and regardless of if, they are actually required. Reactive protocols, in contrast, generate routing control messages only when a path is actually needed. The basic operation of reactive routing protocols, e.g., DSR [1], AODV [2], LOADng [3], is route discovery, illustrated in Fig. 1: a router with a packet to deliver to a destination, and which does not have a valid entry in its routing table for that destination, will issue a Route Request (RREQ) (Fig. 1(b)), diffused through the network (Fig. 1(b)–(d)) so as to reach all other routers. When a router forwards this RREQ, it records an entry in its routing table towards the originator of that RREQ – a reverse route indicating the eventual path from the destination to the originator. If the destination is present in the network, it will eventually receive the RREQ, and respond by a unicast Route Reply (RREP) (Fig. 1(e)), sent along the previously installed reverse route towards the originator of the RREQ. The routers forwarding the RREP will install a forward route towards the destination. Once the RREP arrives at the originator of the corresponding RREQ, a bidirectional path has thus been installed, and is available for use.

If multiple RREQs (with the same sequence number) are received by a destination D from the same source S, D will send a RREP in reply to “the RREQ corresponding to the shortest path”. If an intermediate router x receives two RREQs from the same S, for the same D, and with the same sequence number, x will forward “the RREQ corresponding to the shortest path” and ignore subsequent RREQs, as illustrated in Fig. 1(d) and (e), where the RREQ received by router B from router E is ignored.

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When a link is detected to be broken (typically through a link-layer notification of a data-packet failing to be delivered to a next hop), the detecting router may engage in a route-repair operation – essentially a new RREQ/RREP cycle to discover a path to the destination – and if that fails, issue a route-error (RERR) message to inform the source of the failed data-packet of the error.

This basic Route Discovery process will neither discover nor avoid unidirectional links. If, with reference to Fig. 1, a unidirectional link $A \rightarrow B$ exists on that shortest path, the RREP will never reach $S$ – which will experience a timeout and restart Route Discovery. Subsequent Route Discoveries will face the exact same situation: even if a bidirectional path $S \leftrightarrow C \leftrightarrow E \leftrightarrow B \rightarrow D$ exists, it will not be discovered because of the unidirectional link $A \rightarrow B$.

Excluding unidirectional links is reasonable, even necessary, when the underlying data-link layer itself requires bidirectionality for data traffic forwarding – such as if data-link layer acknowledgement of successful packet delivery are used, e.g., ContikiMAC [4], X-MAC [5], IEEE 802.11b DCF or IEEE 802.15.4-2015 TSCH [6]. Reactive protocols therefore include mechanisms for detecting unidirectional links, and for excluding them from routing paths, and from being used as part of routing protocol operation. These mechanisms are Reverse Bidirectional Acknowledgment (RBC) (expecting Route Reply Acknowledgments, denoted RREP_ACKs, sent in response to RREPs) and Blacklists (ignoring subsequent route discovery messages from a neighbour, who did not send an RREP_ACK in response to an RREP) – both detailed in Section 4.

1.1. Statement of purpose

Even when the underlying layer 2 protocol does not require link bidirectionality, unidirectional links, when present in the network, pose a number of challenges for reactive routing protocols. These links can be detected (by way of RBC) and excluded (by way of Blacklists), at best, at the cost of repeated (costly) Route Discovery operations, but this entails the risk of rendering a network disconnected. Indeed, excluding unidirectional links from route discovery and computation may cause artificial network partitioning and prevent communication between nodes for which bidirectional connectivity is topologically available. Fig. 2 illustrates a case in which routers $A$ and $D$ can communicate with each other (via unidirectional paths $A \rightarrow B \rightarrow D$ and $D \rightarrow C \rightarrow A$), although no bidirectional path between $A$ and $D$ is available.

The exclusion of unidirectional links in this case would partition the network, in which any pair of routers could otherwise communicate, in four isolated regions – one per router. Moreover, detecting and excluding unidirectional links between $A$ and $D$, by using existing mechanisms such as RBC and Blacklisting, would actually not be sufficient to prevent the installation of “false forward routes”, i.e., paths which contain unidirectional links in the direction $A \rightarrow D$.

The objective of this paper is (i) to study the performance characteristics of reactive routing protocols, when facing unidirectional links, (ii) to analyse the cases in which existing mechanisms (notably RBC + Blacklisting) fail to properly exclude unidirectional links from discovered routing topologies and cause false forward routes to be installed, and (iii) to develop and propose mechanisms rendering reactive routing protocols resilient to, and able to properly exploit unidirectional links without relying on any propagation model nor specific layer 2 types when feasible.

This paper proposes two new mechanisms, the Forward Bidirectionality Check (FBC) and the Loop Exploration (LE). FBC is useful for properly identifying unidirectional links in the network (without incurring in “false forward routes”) and LE allows to exploit them, if possible, for route discovery. FBC can thus be used over any data-link technology, whether data-link acknowledgements are used or not. LE, in contrast, is only useful over a data-link technology that does not filter out unidirectional links.

1.2. Paper outline

The remainder of this paper is organized as follows: Section 2 overviews related work on unidirectional links in reactive routing protocols, for the purpose of positioning and providing a context for the work of this paper. Section 3 provides – by way of an analytical model – a study of the performance and behaviour of reactive routing protocols, when exposed to network topologies containing unidirectional links.

Unidirectional links may, in different ways, cause a network to appear disconnected (to the routing protocol, and thus to higher layers). Section 4 first explores the unidirectional link exclusion mechanism of Reverse Bidirectionality Check (RBC + Blacklisting) in detail. This mechanism, part of the RREP forwarding, is found to be insufficient to identify all unidirectional links, and may cause false forward routes (i.e., paths containing unidirectional links in the opposite direction of the intended traffic flow) to be installed as part of the Route Discovery process. To avoid this, this paper
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