Ad Hoc Networks 23 (2014) 121–144

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Proactive versus reactive routing in low power and lossy networks: Performance analysis and scalability improvements

Joydeep Tripathi [a], Jaudelice C. de Oliveira [a,*], J.P. Vasseur [b]

[a] Department of Electrical and Computer Engineering, Drexel University, Philadelphia, PA 19104, USA
[b] Cisco Systems, USA

ARTICLE INFO

Article history:
Received 9 August 2013
Received in revised form 16 June 2014
Accepted 30 June 2014
Available online 9 July 2014

Keywords:
Low Power Lossy Networks (LLNs)
Sensor networks
RPL
LOADng

ABSTRACT

In this paper, the classical debate on suitability of proactive versus reactive routing approaches is revisited, however in the context of their application in Low-Power Lossy Networks (LLNs) as opposed to pure Mobile Ad Hoc Networks (MANETs). We argue that LLNs differ from traditional ad hoc networks not only due to node capacity, but also in the nature of traffic generation and routing requirements. This study aims at a fair comparison between two protocols proposed at the IETF, namely RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) – the proactive candidate, and LOADng (LLN On-demand Ad-hoc Distance vector routing protocol – next generation) – the reactive candidate, making use of real traffic scenarios and topology deployments of varied size, as well as random topologies in the particular case of metrics relating to scalability. Several metrics of interest are investigated, including metrics that have not been paid much attention in the existing MANET literature. In the course of this investigation, we also uncovered non-optimal protocol behavior for the case of large networks and proposed new mechanisms that are shown to improve control plane congestion, as a result improving network lifetime for large scale LLNs. We also derive bounds on control overhead for the two protocols, which indicate that RPL incurs an overhead that is lower than $O(N^2)$ and reduces to $\Theta(N\log(N))$ for a balanced tree structure, whereas LOADng has a total control overhead of $\Theta(N^2)$, irrespective of topology.

1. Introduction

Networks connecting smart, power constrained devices, such as sensor nodes, often operate in highly variable link quality conditions, and have been termed as Low Power and Lossy Networks (LLNs). The challenges in these networks include very low device power and memory, highly varying link quality, frequent link outage, amongst others. Requirements of deployments in smart home, building or industrial automation, communication among Advanced Metering Infrastructure (AMI) meters in a smart grid, etc., relate to delay bound, scalability, and strict time bounds on protocol convergence after any change in topology [1]. Link state routing protocols such as OSPF [2], OLSR [3], IS-IS, and OLSRv2 [4] tend to flood the network with link updates. Since links in LLNs suffer from severe temporal variation and frequent outage, these protocols fail to keep a low control cost overhead [5]. Classical distance vector protocols used in the Internet, such as EIGRP [6], and AODV [7], fail to provide quick recovery from link churn, and frequent topology updates.

A suitable protocol for LLNs therefore needs to abide to strict delay constraints, while maintaining a minimum control overhead, and should be capable of providing quick

* Corresponding author.
E-mail addresses: jt369@drexel.edu (J. Tripathi), jau@coe.drexel.edu (J.C. de Oliveira), jpv@cisco.com (J.P. Vasseur).

http://dx.doi.org/10.1016/j.adhoc.2014.06.007
1570-8705/

recovery from frequent link outage. The IETF ROLL (Routing Over Low power and Lossy network) working group was chartered to identify an IP routing solution for such networks under specific deployment scenarios. After surveying existing solutions, the working group concentrated its efforts on designing and recently standardizing RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) [8], a distance vector protocol with proactive route creation, which provides mechanisms for multipoint-to-point, point-to-multipoint, as well as point-to-point traffic (for a brief overview of RPL, please refer to Section 3). RPL was designed to meet the requirements spelled out in RFC 5826 [1], which defines home automation routing requirements in LLNs; RFC 5673 [9], which defines routing requirements in the industrial setting; RFC 5548 [10], defining the requirements for urban LLNs, and RFC 5867 [11], defining the requirements in building automation. For instance, home [1] and building [11] automation routing requirements call for an end-to-end delay of less than 500 ms and 120 ms, respectively. Simulation studies of RPL in such environments have provided satisfactory results [12–14]. Ref. [12] has also shown that RPL can perform faster repair to converge in case of link churns, a feature mandated in urban [10] and home [1] LLN routing requirements.

Recently, an alternate protocol called LOADng (LLN On-demand Ad-hoc Distance vector routing protocol – next generation) [15], was proposed at the IETF. LOADng is inspired by the AODV protocol, being reactive to incoming traffic (for a brief overview of LOADng, please refer to Section 3). In [16], the authors of LOADng have compared it to a simplified version of RPL and shown the benefits of the former with respect to control overhead, delay, frame collisions, etc. In their comparison, however, RPL has been naively configured (e.g., time period for DAO emissions) resulting in an unnecessarily cumbersome implementation, which lead the authors to simulate it for a shorter period of time and for a completely different traffic pattern than that of LOADng's, therefore jeopardizing the value of the conclusions reached in the paper. In the following, we attempt to summarize the main issues in the study:

- The study considers that DAO messages in RPL are emitted periodically every 15 s, quite an unrealistic assumption for any RPL deployment. A node unicasts DAO packet to the DAG root (in non-storing mode) or multicasts to parent set (in storing mode) only in two cases: (i) a new DAG sequence number is received and the network is undergoing a global repair, and (ii) the most preferred parent is changed as a result of non-reachability to the previous parent.
- The amount of time RPL and LOADng are run differs and moreover the traffic pattern for each is also different. In RPL, data is sent from the "controller" or collection point every 0.1 s, and for LOADng, that duration between successive data transmission is 30 s. As we show in this study, the performance of LOADng depends hugely on data traffic load. Hence we argue that [16] does not provide a fair ground for comparison between the two.
- Furthermore, the deployed network in [16] does not assume any variation in link quality, link outage, or any of the lossy characteristics that a typical LLN posses, leading to 100% delivery of the packets.

This paper aims at a fair comparison between the two protocols using a realistic simulation study that includes an investigation on appropriate configuration parameters for both protocols. Since many metrics on comparison of proactive and reactive protocols are well studied, we concentrate more on issues and metrics specific to LLNs that have not been offered much attention in existing literature, such as temporal variation of control overhead due to multicast traffic, memory consumption, packet length for source routing, and scaling properties. To accomplish this, the RPL simulator that we developed for the study in [13] was extended to include LOADng's implementation described in [15].

While carrying on a detailed comparison study between RPL and LOADng, we also demonstrated for the first time that RPL, though performing better than LOADng, may not behave optimally in large scale networks in terms of memory consumption. As stated in our earlier work [17], we argue that the rationale behind this observation is mainly the congestion caused by the Destination Advertisement Option (DAO) packets from every node to the DAG root during a global repair (see Section 3), or after the DAG root triggers a network-wide address accumulation using a new DAO Trigger Sequence Number (DTSN). This congestion is lethal as it may lead to increased memory requirement, dropped destination advertisement, more control traffic, and loss or delay in important and time-sensitive data or alert packets. Therefore, in order to control the congestion in large deployments of memory constrained nodes, it is essential to design a suitable approach for DAO message emission. In the same work, we have demonstrated that instead of using a fixed universal timer to control DAO emissions, as recommended in the standard, making use of an adaptive timer at each node allows the network to adjust itself to account for topological changes, and adjust each timer in order to avoid congestion and packet drops, specially near the DAG root. In this paper, we further propose a combination of centralized and distributed approach to control DAO emissions in RPL non-storing mode.

This paper's organization as well as a summary of contributions can be described as follows:

- Section 2 summarizes related work on proactive versus reactive protocols, as well as comments on the suitability of geographic protocols. It also summarizes the literature on performance comparison between RPL and other protocols.
- A brief overview of the protocols, RPL and LOADng, is provided in Section 3.
- The details of the simulation model used and traffic generation are described in Section 4. Gathered link quality trace and topology details from 2 networks – one 86 node outdoor deployment, and a 2442 node AMI network were used to emulate real LLN link behavior and network conditions.