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Back pressure congestion control for CoAP/6LoWPAN networks

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ABSTRACT

In this paper we address the design of network architectures for the Internet of Things by proposing practical algorithms to augment IETF CoAP/6LoWPAN protocol stacks with congestion control functionalities. Our design is inspired by previous theoretical work on back pressure routing and is targeted toward Web-based architectures featuring bidirectional data flows made up of CoAP request/response pairs. Here, we present three different *cross-layer* and *fully decentralized* congestion control schemes and compare them against ideal back pressure and current UDP-based protocol stacks. Hence, we discuss results obtained using ns-3 through an extensive simulation campaign for two different scenarios: unidirectional and upstream flows and bidirectional Web-based CoAP flows. Our results confirm that the proposed congestion control algorithms perform satisfactorily in both scenarios for a wide range of values of their configuration parameters, and are amenable to the implementation onto existing protocol stacks for embedded sensor devices.

1. Introduction

In the last few years, we have witnessed considerable advances in terms of protocol design for wireless sensor networking. These have led to a solid understanding of the problems related to channel access, routing and data gathering, delivering efficient protocol stacks and ultimately spurring the standardization of protocols for data collection and addressing.

The work in this paper considers network protocols recently standardized by IETF, namely, CoAP [1] and 6LoWPAN [2], whose combined use permits Web-based bidirectional communications between sensor devices and Internet servers. 6LoWPAN provides header compression and specifies communication profiles that allow the implementation of IPv6 addressing. CoAP is a stateless protocol that is aimed at replacing HTTP for lightweight and resource constrained devices. As such, it implements a reduced set of functionalities with respect to HTTP. While CoAP and 6LoWPAN provide the basis for Web-oriented protocol stacks for embedded devices and natively support UDP traffic, they do not fully address the congestion problem, and only provide some conservative recommendations, as we discuss below in Section 4.

The Internet protocol suite, i.e., TCP/IP, has been designed adopting the "end-to-end argument" [3], which has proven to be very effective in networks of smart terminals operating bulk data transfers. However, TCP congestion control (CC) [4] has been designed with an implicit assumption: data transfers causing congestion are usually long enough to be efficiently controlled through end-to-end CC algorithms. By their own nature, slow start and congestion avoidance are techniques that converge after some time and after a potentially large amount of data has been transferred. However, when the amount of data required to create congestion on the network is very small, these techniques do not provide an efficient solution to the CC problem. In addition to this, TCP is known to be severely impacted by the long delays that are typical of constrained networks.

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In this paper, following the research lines identified in [5], we develop practical congestion control algorithms for constrained Internet of Things (IoT) [6] exploiting 6LoWPAN technology. These networks are characterized by very constrained processing, memory and communication capabilities [7], a potentially large number of nodes, and infrequent communication patterns which very much differ from standard Internet flows.

Our present work quantifies the benefits of implementing congestion control at layer 3 by exploiting practical and lightweight algorithms based on the concept of back pressure routing by Tassiulas and Ephremides [8]. Since their conception, Back Pressure (BP) policies have been extensively explored, leading to distributed theoretical algorithms that achieve optimal throughput performance in distributed networks. Practical applications of these schemes have also been studied in several papers such as [9], which applies a similar policy to the queues of wireless sensor nodes to realize an efficient data collection protocol. However, that solution makes strong use of channel snooping and poses limitations on the implementation of radio duty-cycling (RDC). In [10] the authors propose CODA, a distributed algorithm that uses explicit messages to detect congestion and therefore can also work in the presence of RDC. An evaluation of CODA in 6LoWPAN networks can be found in [11], where the authors measure the loss probability and the number of delivered packets. While these studies on CODA are of interest for the application of congestion control principles in energy efficient networks, some practical issues still remain open, namely: (i) the explicit BP messages are not provided in standard existing protocols, and therefore cannot be used in standard networking stacks and (ii) there is no discussion on some important issues such as the effect of the required number of hop-by-hop retransmissions and of bidirectional CoAP traffic support.

Our main objective in this paper is to systematically compare through detailed simulations different lightweight BP approaches, including existing as well as original algorithms, in order to assess their suitability for the implementation into IoT devices and their benefits in terms of performance gains.

The main contributions of this paper are the following:

- We propose a number of practical and lightweight congestion control algorithms for constrained devices, devising CC policies based on distributed back pressure control, with the objectives of detecting and alleviating network congestion, providing reliability and ultimately controlling the injection of data traffic into the network.
- We present extensive simulation results by comparing the performance of the proposed CC policies with that of ideal back pressure algorithms and showing that layer 3 BP congestion control is feasible on constrained IoT devices, and results in significant performance gains at the expense of minimal additional complexity.
- We present protocols and results for unidirectional and upstream data traffic as well as for bidirectional CoAP flows.

The remainder of this paper is organized as follows. In Section 2 we describe the system model and present our practical BP-based congestion control algorithms for constrained devices. First, in Section 3 we evaluate the performance of these algorithms focusing on unidirectional and upstream data collection. Then, in Section 4 we consider bidirectional communication scenarios such as those arising from CoAP-based Web-services. Finally, we draw our conclusions in Section 5.

2. Back pressure congestion control on 6LoWPAN

In the following, we present some CC designs that are explicitly tailored to constrained networks featuring infrequent communication patterns. Specifically, we propose to perform congestion control actions at the network layer, as this allows the implementation of BP algorithms that work on aggregates of datagrams, i.e., on IP queues. Note that working on aggregates is desirable due to the nature of the traffic found in 6LoWPAN networks, which usually reaches considerable volumes only when the output of multiple nodes is combined. Moreover, this results in a lower complexity in terms of software structure, memory utilization and communication requirements for the control of network queues.

2.1. Node model

Each node has been modeled according to the Internet Host model [12], which classifies protocols into Link, Network, Transport and Application layers.

2.1.1. Link

6LoWPAN has been specifically designed for the IEEE 802.15.4 PHY/MAC [13]. Thus, in our model each node is equipped with an IEEE 802.15.4 radio transceiver operating at 2.4 GHz with a nominal available transmission rate of 250 kb/s. Layer 2 operates according to the IEEE 802.15.4 standard and the total number of transmissions per packet is limited to a maximum of 7.

2.1.2. Network

IPv6 and 6LoWPAN belong to this category; our node has been equipped with a standard layer 3 device (L3D) operating as follows. For each IP datagram, received either from the applications residing in the upper layers or from the radio, L3D first understands whether this datagram has to be delivered to the local host.

As a second step, L3D looks in the Internet routing table, extracts the next hop toward which the datagram has to be sent, and places the received datagram into the layer 3 queue for outbound traffic. This queue is managed according to a First-In First-Out Drop Tail (FIFO-DT) discipline. Note that we account for a single IP queue at layer 3, which is a realistic limitation and is typical of constrained devices.

Our L3Ds implement hop-by-hop layer 3 retransmissions and different BP control algorithms, as specified in Sections 2.2 and 4.1.