TCP Delayed Acknowledgment Techniques for Low-power Multi-hop Wireless Networks

Ahmed Ayadi
Member IEEE
ENIVL, France

ABSTRACT: *Currently, Transmission Control Protocol, which was originally proposed for wired networks, is deployed in multi-hop wireless networks that have memory and energy constraints. The high energy consumption is a strong constraint for the deployment of TCP in low-power multi-hop wireless networks, and especially for low-power and lossy networks such as 6LoWPANs. Some researchers say that TCP is not the bestsuited transport protocol for these kind of networks because of some TCP limitations such as end-to-end retransmissions and acknowledgment frequency. Recently, many works have been proposed to reduce significantly the amount of TCP acknowledgments in order to improve TCP performance.*

In this paper, we present a survey of recently TCP variants that were recently proposed to reduce the TCP acknowledgment. Thereafter, we present a comparative study of the most important solutions based on a metric that we have named energy-efficiency, which takes into account not only the consumed energy but also the TCP throughput.

Keywords: Low-power, Lossy Networks, 6LoWPAN, TCP, Energy-Efficiency, Smart Acknowledgment

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1. Introduction

The Transmission Control Protocol (TCP) is the mostly used reliable transport protocol in the IP-based networks, such as Internet. As described in [11], TCP is a connection-oriented, end-to-end reliable protocol that was originally designed for wired or wireless links. With the exponential growth of wireless devices (e.g., laptops, smart phone, smart TV, etc.), the use of TCP in wireless networks is becoming more frequent and it is not limited to web browsing, sending and receiving emails, but also to many sophisticated applications. However, most of these new devices are mobile and have a strong energy-constraint because of their limited batteries lifetime. In addition, in practice, the TCP performance decreases significantly in multi-hop wireless networks. In fact, the standard TCP assumes that packet losses are due to a congestion (e.g., the total incoming bandwidth to a node exceeds the outgoing bandwidth). Nevertheless, in wireless networks, other kinds of losses are added to congestion, which are interference, collision, route failures, etc. This leads to a high rate of end-toend TCP retransmissions which make the energy consumption very high in multi-hop wireless networks. To remedy this issue, [3] shows that there are three factors that can be optimized in order to reduce the energy-consumption of TCP in these networks, which are : the end-to-end retransmissions, TCP header overhead, and acknowledgment frequency. In this work, we focus on studying the effect of reducing the frequency of sending TCP acknowledgments on the energyconsumption of TCP.

In standard [11], TCP receiver should acknowledge every data segment it receives. Thus, the amount of TCP acknowledgment segments, which are control messages and represent an overhead, is equal to TCP data segments. Delayacknowledgment was proposed after to half the amount of TCP acknowledgments segments; the receiver should wait a short period of 0:2 second before sending an acknowledgment. This mechanism halves the amount of TCP acknowledgment.

Having the amount of TCP acknowledgment is not good enough especially for low-power networks networks such as wireless sensors networks because the ratio of 50 per cent still high. To reduce more and more the acknowledgment frequency, many TCP algorithms [11] has been proposed to send less TCP acknowledgment in a TCP session. In this paper we present a survey of the most important ideas and we especially focus on TCP-DCA [5] and TCP-TDA [4]. We present in detail these two algorithms and we compare their performance using simulation.

The remainder of this paper is organized as follows. Section II presents a brief overview of the related works in the area of TCP performance over multi-hop wireless networks. Section III shows simulation results and a summary. Finally, in Section V, we give our conclusions and provide directions for future work.

2. Delayed Acknowledgment Algorithns for Multi-hop Wireless Networks

Many works have studied the performance of TCP over multi-hop wireless networks. Firstly, S. Xu and T. Saadawi [15] compared the existing versions of TCP algorithms in multi-hop wireless networks with string topology. Their simulation results show that, in most cases, the Vegas version works best and maximizes the throughput in multi-hop wireless networks. Moreover, S. Xu and T. Saadawi showed that the TCP connection can gain 15 to 32 per cent goodput improvement by using the TCP delayed acknowledgment option. In [9], L. Heng and G. Ai-huang investigate the energy consumption of different version of TCP and their simulation results indicate that SACK version is the most energy efficient protocol.

Gerla et al. [8] were the first who have investigate the interaction between MAC layer and TCP in multi-hop wireless networks in three different types of topologies. Their study showed that TCP performance decreases significantly in CSMA networks when the distance between sender and receiver is larger than 2 hops and the TCP advertised window is fixed to more than 1 packet. They explained this result by the hidden terminal problem caused by the collisions of TCP DATA segments and TCP ACK segments. In fact, as the TCP windows increased, multiple TCP DATA segments and multiple TCP ACK segments travel on the path in the opposite direction, creating interference and collisions. In [12], Tang et al. extends [8] works by studying the impacts of the MAC layer mechanisms such as using the ACK frame, Collision Avoidance (CA), and Request to Send (RTS)/ Clear To Send (CTS) on TCP performance. This study conclude that using the distributed coordination function (DCF) of the IEEE 802.11 standard which is the combination of CSMA, CA, ACK, and RTS/CTS provides the best performance of TCP in terms of goodput.

In [7], Fu et al. started from and then extended the previous works and showed that a good choice of a TCP widows size depending on the number of hops between the source and receiver improves TCP throughput. The main objective of this study was to found the optimal windows size at which TCP achieves the goodput via a best use of the shared wireless channel. Their simulations and analysis show that a TCP window of $\frac{h}{4}$ is the best choice in string topology multi-hop wireless networks, where h is the number of hops between the source and the receiver.

Altman et al. [2] studied the impact of delayed acknowledgment on the TCP performance in multi-hop wireless networks. They showed that increasing the standard delayed ACK value ($d = 2$) up to $3 - 4$ packets increases TCP throughput by around 50 per cent. Moreover, they proposed a basic delayed ACK approach which they called "*Dynamic Delayed ACK*" (DDA). TCP-DDA algorithm increases d gradually with the sequence number of the acknowledgment segment. In addition, DDA limit the The advertised window to only 4 packets.

R. de Oliveira and T. Braun [10] proposed a dynamic adaptive acknowledgment (DAA) strategy for minimizing the number of ACKs. The TCP-DAA algorithm proposes to adapt the TCP window and the timeout interval. The TCP receiver computes a smoothed packet interval ($\bar{\delta}$) and then set the timeout interval (t_i) as $t_i = (2 + k) * \bar{\delta}$, where k is a timeout tolerance factor. k defines how tolerant the receiver may be deferring its transmission beyond the second expected DATA packet. The TCP Window is initialized with one packet size, and then increased by a startup speed factor ($l = 0.3$ packet) till a certain threshold. After the startup phase, the TCP Window size is increased by one packet size. TCP-DAA is more tolerant to packet delay variations by having the regular RTO (retransmission timeout) at the sender multiplied by a factor of 5. Their simulation results shows that TCP-DAA outperforms TCP-DDA not only of chain topology but also in grid topology.

J. Chen et al. [5] proposed an adaptive delayed acknowledgment mechanisms TCP-DCA (Delayed Cumulative Ack). TCP-DCA removes the limit of delayed window of four packets imposed by TCP-DAA and adapt the delay window limit depending of the path length. TCP-DCA proposes that the receiver compute the inter-arrival of the TCP data segments and then adapt the delay of sending a TCP acknowledgment. The delay window limit is equal to the congestion window if the number of hops between the sender and the receiver is less than three. Moreover, The delay window limit is equal to five if the number of hops is more than three and less than nine, and equal to three if the number of hops is more than nine hops. In addition, TCP-DCA algorithm puts the congestion window into the advertised window.

B. Chen et al. [4] proposed TCP-TDA, a new TCP algorithm that uses the ACK-delay timeout as a trigger for sending an acknowledgment. In fact, the TCP-TDA receiver always wait until this timeout event occurs to generate an ACK, no matter how many in-order packets it receivers during the timeout period. TCP-TDA set up a large delay window (equals to 25), thus it makes the ACK-delay timeout to be the main generator of ACKs. Moreover, the authors set the timeout time at 500 ms (default value is 200 ms). In addition, when the congestion window is small, TCP-TDA proposes to put the congestion windows in the advertised window, so it allows to inform the receiver about the current value of the congestion window. The difference between TCP-TDA and TCA-DCA is that it does not need to count the path length. Moreover, simulation results show that TCP-TDA improves TCP throughput up to 205 percent.

Parameters	**Value**
Transmitted Data Size	48kbytes
Maximum Segment Size	48bytes
TCP Algorithm	NewReno
MAC Layer	IEEE 802.15.4
Channel Number	26
PHY bitrate	250kbps
Transmission Range	50m
Transmit Power	1.0 mW
Routing Protocol	AODV

Table 1. Simulation Parameters

3. Evaluation and Discussion

To evaluate and compare the discussed TCP variants, we have implemented TCP-TDA and TCP-DCA on INETMANET [14], a framework of the OMNET++ [13] network simulator. We compare TCP to TCP-DCA and TCP-TDA in a simple chain topology and more complex topologies such as grid and cross topology. We have performed simulations with unidirectional TCP data transfers. The TCP algorithm used in our simulation is NewReno, which is currently the most deployed one. We have used the AODV (Ad hoc On-demand Distance Vector) routing algorithm in our simulations. Table I contains values of all parameters. Our simulations consist of ten runs, and the reported results are the average of the ten independent runs with different random seeds.

To measure the amount of consumed energy by wireless nodes, we apply the following energy model. A wireless node is in one of four states : Transmit, Receive, Sleep or Idle. Table 2 contains the power value of each state.

3.1 Evaluation metrics

To compare performance of different TCP variants, we compute the consumed energy and the throughput by each TCP variatns.

Moreover, we add another metric must take into account the energy consumption and the throughput of a TCP connection. We denote by *Eff* this metric by which is equal to

$$Eff = \frac{Throughput}{Consumed\ Energy}$$

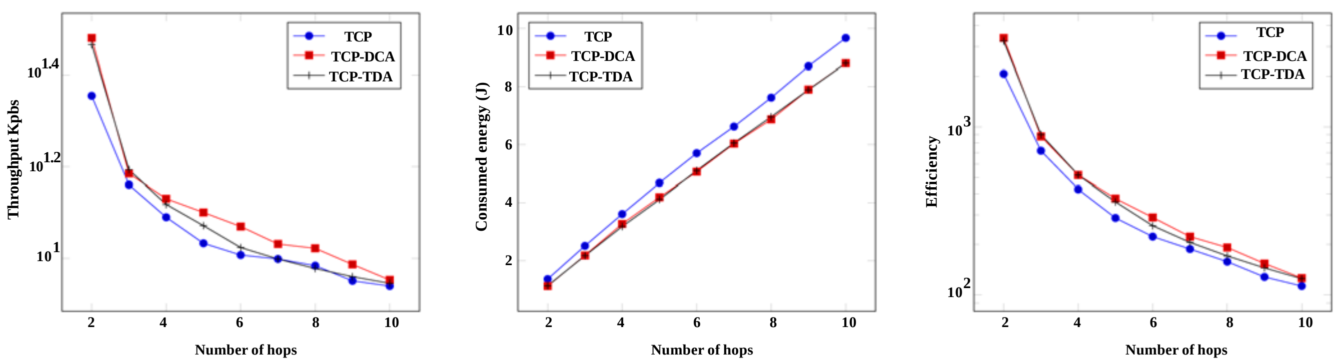
This metric increases when the throughout of TCP increases or when the energy consumption of a TCP connection decreases. For example, two TCP connections that consume the same amount of energy, the more efficient is that which reduces the transfer duration (i.e., it increases the throughput). Moreover, the inverse of these metric represent the energy cost of sending 1kps.

Mode	Value
Voltage	3V
Transmit Power	17.0 mA
Receive Power	19.6 mA
Idle Power	1.38 mA
Sleep Power	0.06 mA

Table 2. Energy Model of Nergy Model of Wireless Nodes

3.2 Chain topology

We start our evaluation with a chain topology as shown in Figure 2 where node n is in the transmission range of node $n-1$ and $n+1$. The distance between two neighbor nodes is 30 meters. The TCP sender (source) sends 1000 TCP data segments (521kb) to the TCP receiver.We compute the transfer duration and the energy cost of both scenario: single TCP flow and multi TCP flux.



(a) Throughput (b) Consumed energy (c) Efficiency

Figure 1. Single flow scenario: Throughput, energy-consumption, and energy-efficiency of TCP variants over chain topology

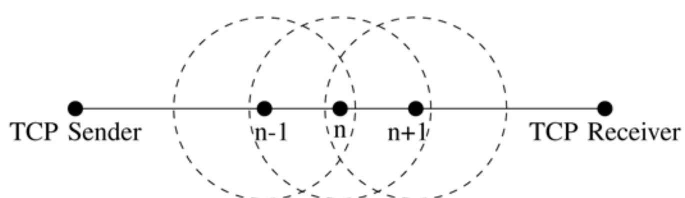


Figure 2. Chain Topology

3.2.1 Single TCP flow

Figure 1 (a) shows that our results are close to the ones presented in [4]. In fact, TCP-TDA and TCPDCA increase more the TCP throughput than TCP. However, we can see that from 6 hops, TCP-DCA outperforms TCPTDA. In fact, TCP-TDA does not limit the delayed window size which allows the TCP source to send more segments before receiving an acknowledgment. This may lead to a lot of end-to-end retransmissions especially when the end-to-end error rate increases. We assume that the source node has a large sending buffer to do that. Figure 1 (b) shows the consumed energy by all wireless nodes in different TCP variants. We can see that all TCP delayed acknowledgment variants are more energy efficient than standard TCP and reduce the total consumed energy. The reduction ratio is about 20 percent when the number of hops between the source and the destination is equal to 2 and by about 10 per cent when the number of hops is equal to 10 . Moreover, Fig. 1 (c) shows that TCP-DCA is more energy-efficient than TCP-TDA because it adapts better the delay window limit depending on the network size.

3.2.2 Multiple TCP flows

In this section, we retain the same topology as the previous section, however, we will study the impact of multiple flux on the energy efficiency. Indeed, we run 2, 4 and 6 flows between the source and destination. For each scenario, we compute the TCP throughput and energy consumption and thus the efficiency.

Figure 3 shows that TCP delayed acknowledgment algorithms are more efficient than TCP in all scenarios. Moreover, Figure 3 shows that TCP-TDA is increases more efficient that TCPDCA because TCP-TDA does not limit the delayed window size which allows the TCP source to send more segments before receiving an acknowledgment. However, this assumes that the source node has a large sending buffer to do that.

3.2.3 Cross topology

In the cross network shown in Figure 4, we run two flows; one flow go horizontally, and one flow go vertically. We vary the number of hops between the source and the destination and we compute the aggregate efficiency for different TCP variants. Figure 5 shows that TCP variants are more efficient that TCP, and especially in the 6 flows scenario. This is due to the reduction of TCP acknowledgments, and thus less channel contention and collision between TCP data segments and TCP acknowledgments.

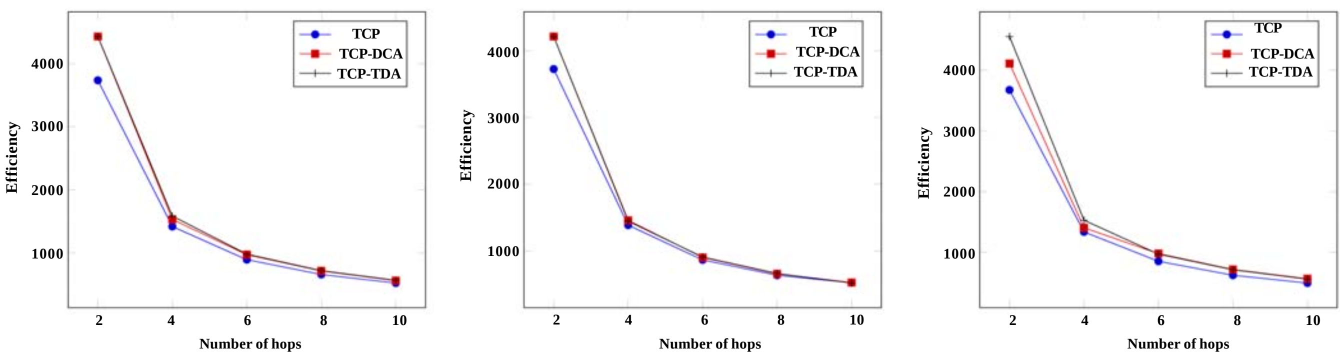


Figure 3. Multiple flows scenario: comparison between TCP, TCP-TDA and TCP-DCA in terms of efficiency

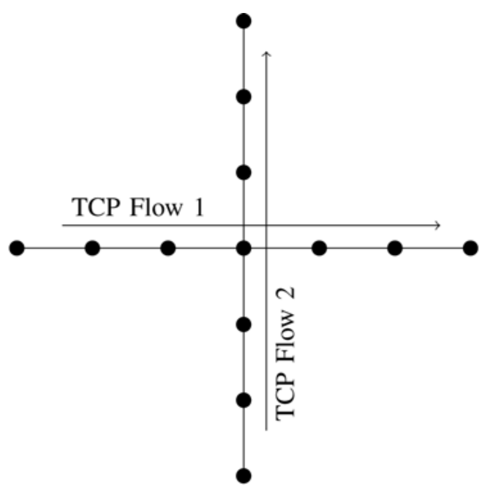


Figure 4. Cross topology

3.2.4 Grid topology

Now, we focus on the second complex topology: grid topology. Figure 6 shows a example of 5×5 grid topology. We run 4 flows;

three flow go horizontally, and only one flow go vertically. Figure 7 shows the aggregate efficiency of TCP variants. TCP-DCA is the most efficient efficient algorithms in all scenarios. As described in the previous section, these results can be explained by a better choice of the delayed acknowledgment limit chosen by TCP-DCA. In fact, in many cases, allowing the TCP source to send more TCP date segments before receiving an acknowledgment may lead to a luck of TCP flow control.

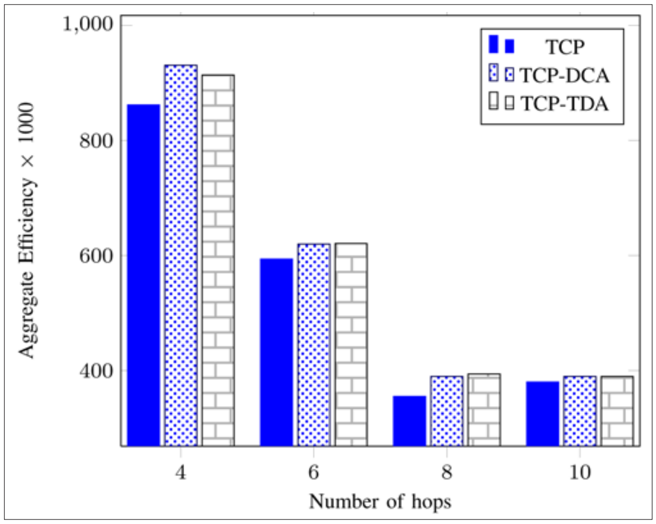


Figure 5. Cross topology scenario: Aggregate Efficiency of TCP variants

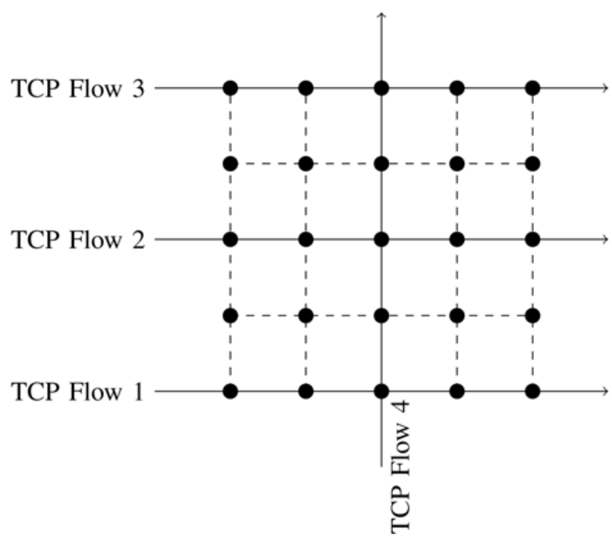


Figure 6. Grid Topology

4. Summary

As it was well detailed in Section II, recent researchers, that worked to improve the performance of TCP in multihop wireless networks, have proposed algorithms to reduce TCP acknowledgments. The main idea of these algorithms is to delay the acknowledgment even after the reception of two segments. The two more efficient delayed acknowledgment algorithms are TCP-TDA and TCP-DCA. TCP-TDA is simpler to implement (compared to TCP-DCA) and does not require that the receiver computes the segment inter-arrival times (i.e., the time between consecutive segment arrival). Moreover, TCP-DCA requires that the sender knows the number of hops between itself and the receiver.

The main drawback of TCP-TDA and TCP-DCA is that it requires the use of the advertised window, which should normally inform the sender about the receiver buffer capacity, to inform the receiver about the number of segments after which it must send an acknowledgment. The solution is possible for unidirectional data transfer (where one device can communicate with each other but only one direction at a time (i.e., not simultaneously)). These disable some of the most-used TCP-based applications such as SSH and HTTP. Instead of sending the size of the congestion window, we propose to use one of the reserved bits of the TCP header for requesting an acknowledgment. The idea was firstly proposed by A. Oppermann[1] and then discussed by [6] to reduce the TCP acknowledgment congestion.

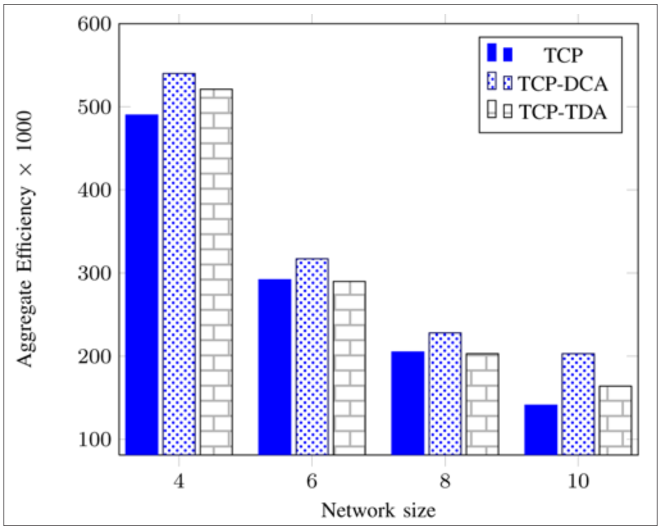


Figure 7. Grid topology scenario: Aggregate energy efficiency of TCP variants

Reducing the TCP acknowledgment ratio would have a bad impact on TCP performance. The TCP congestion window increases by a constant amount for each arriving acknowledgment. The TCP delayed acknowledgment would reduce the TCP throughput by reducing the ACKs and then increase the transfer duration. In [1], Allman proposes another congestion control mechanism for coping with delayed acknowledgments. The main idea was that the TCP congestion window should be increased based on the number of bytes acknowledged by the arriving ACKs. In order to improve delayed acknowledgment algorithms performance, we propose to apply the same idea, even if the number of delayed acknowledgments is higher than two segments. In addition, the TCP SACK option can be used to signal if one or more segments are lost by showing the received segments.

5. Conclusion

This paper has studied the impact of reducing the frequency of TCP acknowledgments on the energy consumption over multi-hop wireless networks. The paper presented a survey of the recent TCP algorithms have been proposed to reduce the acknowledgment frequency, then a comparative study of the two more efficient TCP algorithms which are TCP-TDA et TCP-DCA. Our study showed that both algorithms permit to reduce the total consumed energy of TCP from 10 to 20 per cent. This ratio depends especially on the network topologies and the number of hops between the source and the destination. Finally, we discussed some ideas that can further improve the efficiency of both solutions.

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