

# Adaptive TCP Segment Size Control for Reducing Energy Consumption in 6LoWPANs

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**Abstract**—In high data rate wireless networks such as IEEE 802.11 and IEEE 802.16, it is well-known that sending a long transmission control protocol (TCP) header brings the advantage of overhead and energy consumption reduction. However, in Low power and Lossy Networks (LLNs) such as 6LoWPANs, the long TCP segment is split into short IEEE 802.15.4 frames to adapt with the lossy networks. The main drawback of this approach is that the TCP segment is lost when one of the frames is lost. With uncontrollable and unpredictable bit error rate (BER) of wireless channel, the TCP segment size, however, can be adjusted depending on the BER to reduce packet loss ratio. In this paper, we study the relationship between TCP segment size and energy consumption, and the trade-off of sending long or short TCP segments. We propose a new TCP Segment Size Adaptation (TSSA) algorithm that adaptively adjusts the segment size based on BER of wireless channel. We show by simulation that the algorithm converges quickly to the optimal maximum segment size (MSS) value that could reduce the energy consumption.

**Index Terms**—Multihop Wireless Networks, Low power and Lossy Networks, Energy Efficiency, TCP.

## I. INTRODUCTION

IP-based LLNs are composed of many wireless nodes that are subject to strong constraints on power and computing capabilities. Moreover, the link-layer technology like IEEE 802.15.4 [13], that is often used in wireless LLNs, imposes very low limits on link frame sizes.

The LLNs such as wireless sensor networks (WSNs) do not always require full link reliability. However, there are several cases of LLNs applications in which reliability of data delivery can be critical, e.g., over-the-air software updates [4], [9], [17]. In such cases, the TCP [10] is a common choice for ensuring an end-to-end reliable transport in IP-based LLNs.

TCP is the most used transport protocol in Internet Protocol (IP) networks. It provides a reliable transfer service for all kinds of applications. TCP can manage data that is damaged, duplicated, lost, or delivered not in order. This is achieved by assigning a sequence number to each byte transmitted and requires a positive acknowledgement (ACK) from the recipient. If the TCP ACK segment is not received within the time interval, the data segment is retransmitted.

Many factors affect the energy consumption of a reliable transport protocol, e.g., wireless channel losses, frame collisions, link-layer reliability, number of links or hops between a source and destination, and the maximum size of link-layer

frames (such as 127 bytes used in the IEEE 802.15.4). Such frame length may require fragmentation of IPv6 datagrams before sending them over the LLNs. The IETF 6LoWPAN working group, therefore, has defined a new protocol layer between the IPv6 and the medium access control (MAC) layers, i.e., the 6LoWPAN layer. The 6LoWPAN layer task is to compress the IPv6 header and fragment the IPv6 packets into short IEEE 802.15.4 frames. If the size of a TCP segment exceeds the maximum allowed length, the 6LoWPAN layer then fragments it to make it fit into IEEE 802.15.4 frames. However, this fragmentation leads to a serious problem when a frame of the original segment is lost. In such case, the source node retransmits the whole lost transport layer segment. Sending short TCP segments has an advantage of no fragmentation required. However, the use of a small segment size increases the number of TCP segments, and consequently, the number of TCP ACKs. Furthermore, using small segment size increases the overheads of the TCP headers and this, in addition to the small size of MAC frames, may result in a very low protocol efficiency.

In this work, we study the energy cost reliability when TCP is used in multihop wireless LLNs. The trade-off of sending long and short TCP segments is analyzed and its effect to the energy-efficiency. We will illustrate some main TCP issues in IPv6-enabled LLNs that is based on the 6LoWPAN protocols [11]. We propose a new TCP Segment Size Adaptation (TSSA) algorithm that could adapt dynamically with TCP segment size according to channel conditions.

The reminder of this paper is organized as follows. Section II gives a brief overview of some related work of energy-efficiency TCP performance in LLNs. Section III presents the relationship between TCP segment size and BER. Section IV presents the TSSA algorithm followed by simulation work in Section V. The section analyzes the consumed energy and compares the performance of TSSA with Dynamic MSS. Finally, in Section VI, we conclude this paper with a summary of the results.

## II. RELATED WORK

There exist many studies of the performance of TCP in multihop wireless networks (see for example [6] and references therein), though many of them are mostly concerned with

parameters like TCP throughput [5], [14], and with protocol enhancements aimed at improving such performance metrics. Some papers focus on the computational cost of TCP (e.g., [18]), while others (e.g., [7], [12], [19]) compare the energy efficiency of different TCP congestion control algorithms (like SACK, Tahoe, Reno and NewReno) over wireless networks.

In [8], Lilakiatsakum and Senevirane propose an energy-efficiency metric to compare the performance of different versions of TCP. The metric is the ratio of the amount of bits sent by all nodes with the size of the application data. Note that, in our work, we adopt a variant of this metric (the total amount of bits sent) but we consider a fixed value of the application data size.

Choi et al. [2], [3] propose Dynamic MSS (DMSS), a scheme that reduces the performance drop of TCP by adapting the segment size dynamically. They propose a simple scheme adapting the MSS according to wireless channel conditions. Two different values of MSS are defined, i.e., small MSS and large MSS. The small MSS is used in bad channel condition and its size allows it to fit into a link layer frame. On the other hand, the large MSS is used in good channel condition and its size is determined by the path maximum transmission unit (MTU) discovery mechanism of TCP. The frame error rate is used as an indicator of channel states. The paper uses the frame error rate (FER) as an indicator of the channel state. The scheme judges that the channel condition is bad when the error rate is over the threshold, and the state is good when the rate is under the threshold. The authors consider the FER of 5% as a threshold to decide whether the channel is in good or bad state. However, the proposed scheme does not consider that sending long TCP segment, which is split into small fragments, increases the error rate due to collisions between the independent link-layer frames.

### III. RELATIONSHIP BETWEEN TCP SEGMENT SIZE AND BIT ERROR RATE

Today, the dominant protocol stack is the TCP/IP reference model. TCP/IP was originally designed for wired links, characterized by high bandwidth, low delay, low probability of packet loss (high reliability), static routing, and no mobility. On the other hand, in wireless domain, performance and resources are limited by the time-varying channel performance, the scarce availability of transmission spectrum, the employed modulation type and the limited transmission power. Loss probability experienced by packet transmission in wireless medium is in general higher than that in wired links. The BER varies from  $10^{-9}$  to  $10^{-6}$  for wired channels, whereas, in wireless channels it varies from  $10^{-6}$  to  $10^{-3}$ .

Indeed, the packet error rate (PER) at the link layer depends on the BER performance on the physical channel. For large packets (link layer segments) with size of 1500 bytes, PER is significantly less than 1% in wired networks, whereas it can range from 1% to 12% in wireless. Such PERs are unacceptable for most of natively wired network protocols such as TCP. In order to counteract such range of variation

in terms of BER and PER, we study the impact of BER and MSS on the energy consumption in TCP scenario.

The PER of a message depends on the BER and the size of the message. Here, we assume that all bits have independent random errors, each bit being correctly received with a probability of  $1 - \text{BER}$ . Moreover, we assume that a link layer frame transmission fails as soon as one bit is erroneously received. The probability of an error for a TCP data message, i.e., segment error rate (SER) or frame error rate (FER) is thus:

$$\text{SER} = \text{FER} = 1 - (1 - \text{BER})^S \quad (1)$$

where  $S$  is the frame size (in bits), which is equal to

$$S := \text{MSS} + \text{TCPH} + \text{IPH} + \text{MACH} + \text{PHYH}$$

where TCPH, IPH, MACH and PHYH are the size (in bits) of the TCP header, IP header, MAC header and Physical header, respectively.

However, in IEEE 802.15.4, the maximum frame size is 127 bytes and the MTU of the 6LoWPANs has a size of  $(127 - \text{MACH} - \text{PHYH})$  bytes. Thus, all TCP segments with size greater than the MTU are split into several frames and transmitted independently. With this requirement and manipulation, we obtain SER as follows:

$$\text{SER} = 1 - (1 - \text{FER})^N = 1 - (1 - (1 - \text{BER})^{S'})^N \quad (2)$$

where  $S'$  is

$$S' := \frac{\text{MSS} + \text{TCPH} + \text{IPH}}{N} + \text{MACH} + \text{PHYH}$$

and  $N$  is the number of the fragments of the original TCP segment which is equal to

$$N := \frac{\text{MSS} + \text{TCPH} + \text{IPH}}{\text{MTU}}$$

### IV. TCP SEGMENT SIZE ADAPTATION

In this section, we describe a novel TSSA algorithm that could adapt the TCP segment size with the frame loss ratio. Fig. 1 shows with more details a diagram describing the TSSA algorithm.

The main idea of the algorithm is to reduce the MSS when BER of the channel increases and to increase the MSS when BER decreases. The algorithm should be reactive to the channel condition changes. The TSSA algorithm reduces the energy-consumption of TCP connection by reducing the packet error rate, and thus increases the lifetime of the wireless network. If the channel error rate increases, the TSSA adjusts the segment size from a long segment size to a small one. Moreover, if the channel error rate decreases, the TSSA adjusts the segment size from a short segment size to a long one. TSSA keeps the MSS of TCP, that was negotiated on the beginning of the TCP connection and does not allow to send a segment with a size larger than the MSS.

The TSSA algorithm starts by a **Fast Start** phase, where the MSS is doubled until a TCP segment is lost. This phase will rapidly increase the size of MSS if the BER is low. The

first phase ends after the first lost and then starts the second phase.

The second phase tries to adjust the MSS to the best choice based on the losses. The increasing and decreasing value is the link layer MTU. The TSSA algorithm increases the MSS by an MTU after  $S\_MAX$  successful transmissions (i.e., the source node receives  $S\_MAX$  TCP ACKs). In our work, we have chosen  $S\_MAX$  equals to ten. A big value of  $S\_MAX$  makes TSSA algorithm less reactive to the channel condition changes. However, a low value of  $S\_MAX$  may increase the SER due to unsuccessful attempts to increase the MTU. After a loss, the TSSA reinitialize  $S\_MAX$  to zero and after two losses, the TSSA reduces the MSS by MTU.

are performed for 30 runs, and each of the reported results represents the average of the 30 runs.

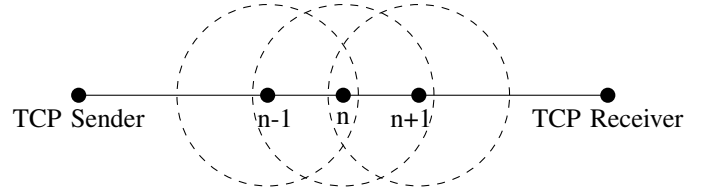


Fig. 2. Chain Topology

TABLE I  
SIMULATION PARAMETERS

Parameter	Value
Number of hops	5
MAC layer protocol	CSMA-CA
Link layer protocol	IEEE 802.15.4
Physical layer bitrate	250 kbps
Maximum Link layer retransmissions	3
MAC Ack Size	40 bits
MAC header	120 bits
IP header	160 bits
TCP header	160 bits
File size	512 kbytes
Transmit Power	50.2 mW
Receive Power	59.1 mW

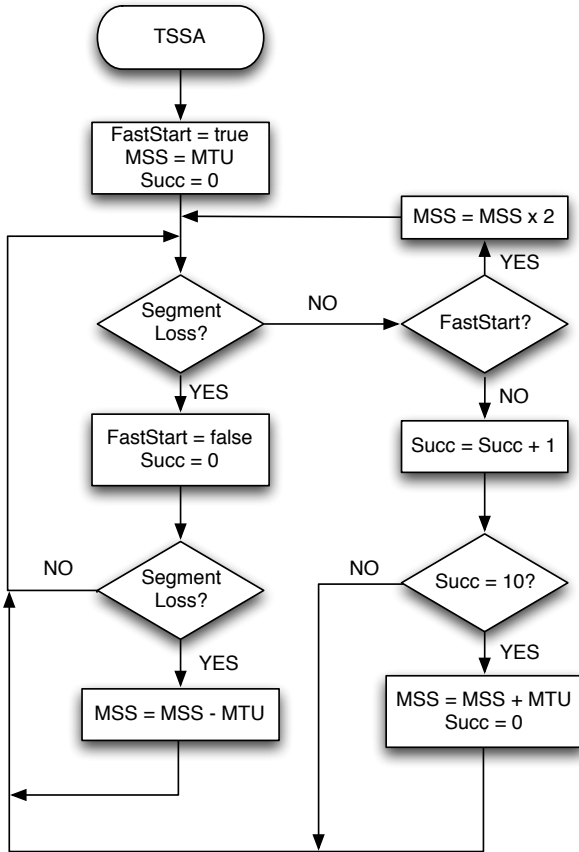


Fig. 1. TCP Segment Size Adaptation Algorithm

## V. SIMULATION RESULTS

### A. Simulation Model

To evaluate the performance of the TSSA algorithm, we implemented the TSSA and DMSS on INETMANET [15], a framework of OMNET++ [16] simulator. Simulations are run for unidirectional TCP data transfers over a chain topology as shown in Fig. 2. The dashed circles represent the transmission range of a node in this topology. Node  $n$  is in the transmission range of node  $n - 1$  and  $n + 1$ . Table I gives some values of the parameters used in all scenarios. The simulations

### B. Discussion

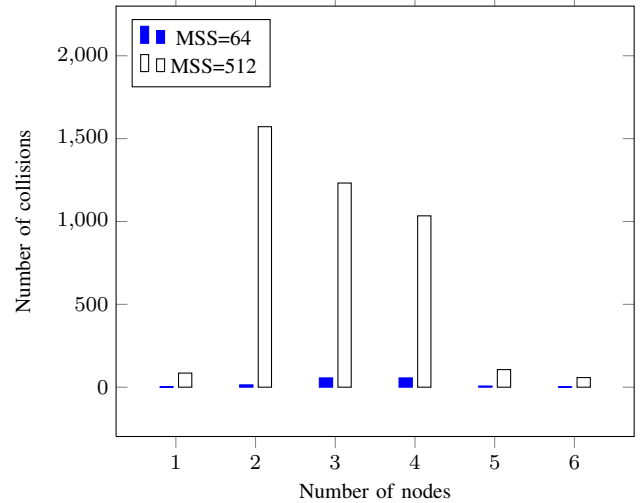


Fig. 3. Number of collisions in a multi-hop scenario

1) *The used of short TCP segment increases the collision ratio:* To show the importance of collisions in wireless networks, we simulate two TCP scenarios in ad hoc network with 5 hops between the source and destination node. We compare with an analytical model [1] which is based on BER for computing the performance of TCP over wireless networks. The analytical models do not take into account the impact of collisions in such network. In the first scenario, the

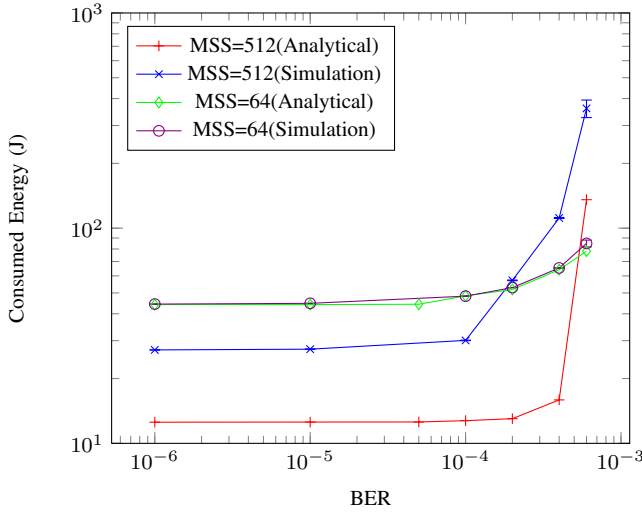


Fig. 4. Consumed energy by simulation and analytical model

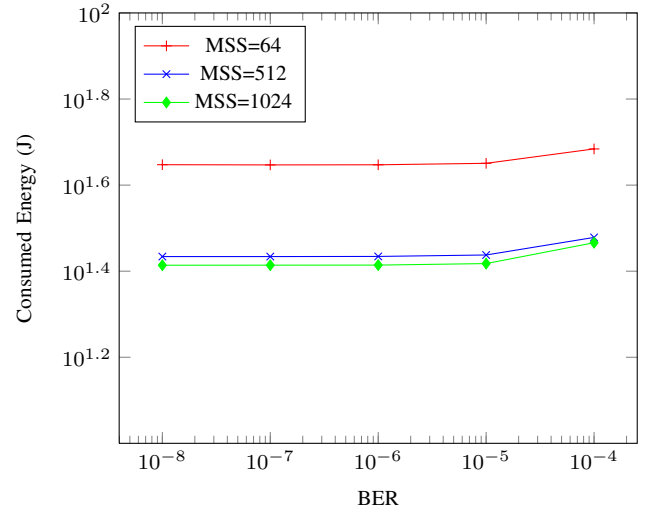
TCP sender sends short TCP segments ( $MSS = 64$ ) which are encapsulated in one IEEE 802.15.4 frame. However, in the second scenario, we choose a long MSS value of 512 bytes. In this scenario, the TCP segment is split by the 6LoWPAN layer into 8 frames. These frames are sent independently over the wireless medium. We compute the number of collisions per node in the two scenarios and the total consumed energy.

Fig. 3 shows the number of collisions recorded by the wireless nodes. The node number 1 is the sender and the node number 6 is the receiver node. Nodes from 2 to 6 are in order from the sender node and the receiver node. Fig. 3 shows that the number of collisions is very high when a TCP segment size is equal to 512 bytes especially in the intermediate nodes. The intermediate nodes closer to the source have more collisions than those far near the receiver. The great number of collisions is due to the fact that sending independent frame in the network may cause collisions especially when the MSS is of greater size.

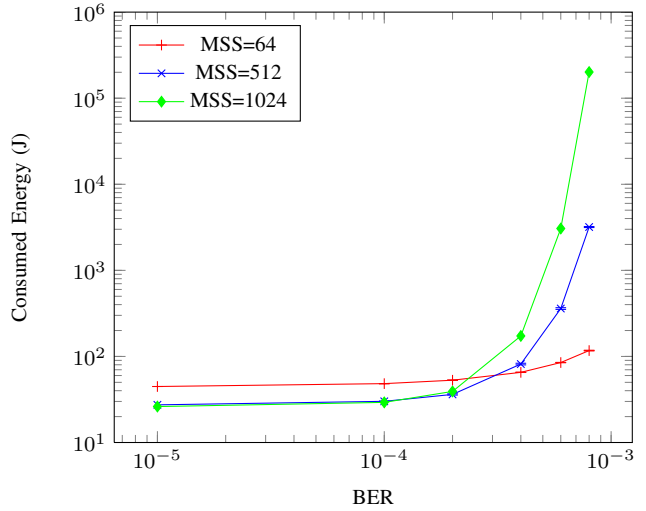
Fig. 4 shows the consumed energy by the wireless nodes in the two previously described scenario. Fig. 4 gives a comparison of the total consumed energy obtained by simulation versus the computation by analytical model. The figure shows that simulation and analytical model results are very close if the MSS is equal to 64. However, the difference is greater in the second scenario. The results confirm that the consumed energy is higher for the simulation result since it takes into account the collisions between the link-layer fragment of the TCP segments.

2) *TSSA reduces the total consumed energy*: We compare the two scenarios of a TCP segment transmission based on the TCP MSS value adapted with the DMSS and TSSA algorithms, respectively. We use three different values of the MSS: 64, 512 and 1024 bytes.

The graphs in Fig. 5 show that using long TCP segment in low-lossy network like the wired network (where the  $BER \leq 10^{-4}$ ) is more energy-efficient than in high lossy network.



(a) Low lossy network ( $BER \leq 10^{-4}$ )



(b) High lossy network ( $BER \geq 10^{-4}$ )

Fig. 5. Consumed energy using long MSS in Low- and High- lossy networks

It is noticed that if the channel becomes noisier and the BER increases, the energy consumption with long TCP segment increases exponentially. This is due to the end-to-end retransmission of lost segments, which are sent in small IEEE 802.15.4 fragments and the loss of one of these fragments leads to a new end-to-end retransmission. However, sending a short TCP segment is more energy-efficient in very high-lossy environment.

Fig. 6 presents the consumed energy of the wireless nodes for both TSSA and DMSS algorithms. The figure shows that the energy consumptions in the two scenarios are very close in networks with a low loss rate and very high loss rate. However, the TSSA has a low energy consumption when the BER is from  $10^{-5}$  to  $4 \cdot 10^{-4}$ . The difference is due to the fact that DMSS jumps to the size of the smallest MSS while in this case the value is not the optimal. TSSA algorithm adapts progressively the value of MSS with the increase of the BER.

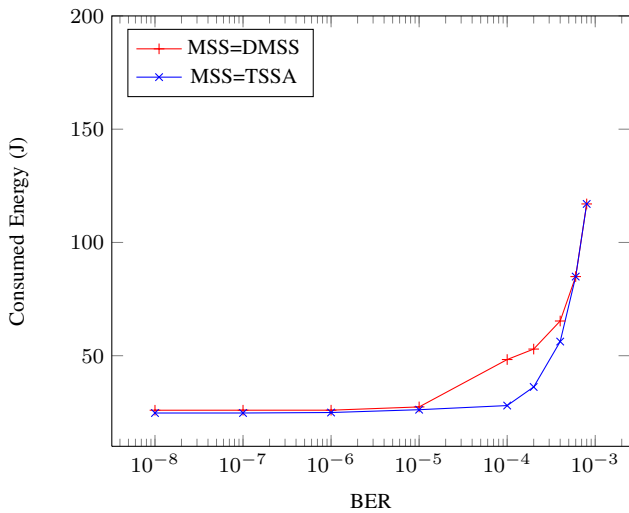


Fig. 6. Consumed Energy by TSSA and DMSS nodes

The figure shows that TSSA converges quickly to the best value of MSS.

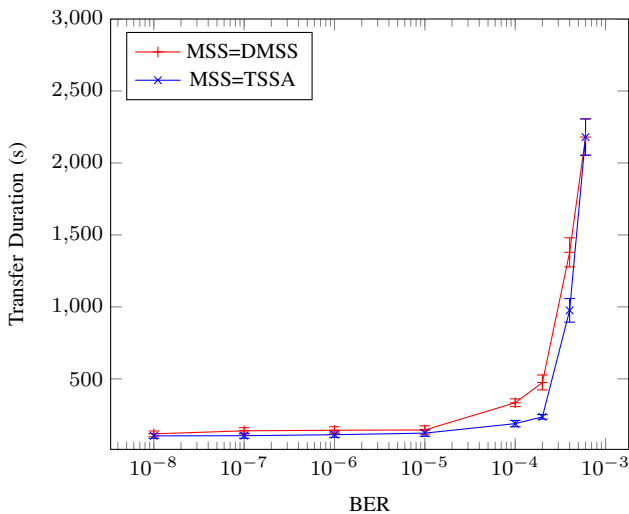


Fig. 7. The transfer duration by TSSA and DMSS

3) *TSSA increases TCP throughput*: Sending a file is not the main purpose of LLNs deployment. However, if the transfer duration takes long time, the performance of the LLN would decrease. Using the same topology defined above, we compute the transfer duration of the same file using TSSA and DMSS. Fig. 7 shows that in low-lossy and very-high-lossy environment, the TSSA performance are near the DMSS performance. However, the TSSA reduces the transfer duration by about 15-40% compared with the DMSS if the BER is in between  $10^{-5}$  and  $4.10^{-4}$ . This performance is due to the quick convergence of TSSA to the optimal MSS.

## VI. CONCLUSION

This paper has presented a novel algorithm for adapting the TCP maximum segment size in Low power and Lossy Networks (LLNs). The main idea of TSSA is to adapt the TCP MSS to the best value that reduces the energy consumption. We implemented the TSSA and a legacy algorithm named DMSS on OMNet++ network simulator. Our simulation results show that TSSA algorithm is more energy-efficient than DMSS whatever the wireless channel condition.

## VII. ACKNOWLEDGEMENTS

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