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Evaluating transport protocol performance over a wireless mesh backbone

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ABSTRACT

IEEE 802.11n wireless physical layer technology increases the deployment of high throughput wireless indoor mesh backbones for ubiquitous Internet connectivity at the urban and metropolitan areas. Most of the network traffic flows in today's Internet use 'Transmission Control Protocol' (TCP) as the transport layer protocol. There has been extensive works that deal with TCP issues over wireless mesh networks as well as noisy wireless channels. Further, IEEE 802.11n is well known for its susceptibility to increased channel losses during high data rate communication. This paper investigates the dynamics of an end-to-end transport layer protocol like TCP in the presence of burst and correlated losses during IEEE 802.11n high data rate communication, while maintaining fairness among all the end-to-end flows. For this purpose, we evaluate four TCP variants-Loss Tolerant TCP (LT-TCP), Network Coded TCP (TCP/NC), TCP-Horizon and Wireless Control Protocol (WCP), where the first two protocols are known to perform very well in extreme lossy networks, and the last two are specifically designed for mesh networks. Our evaluation shows that WCP performs better in a IEEE 802.11n supported mesh networks compared to other three variants. However, WCP also results in negative impact at high data rates, where end-to-end goodput drops with the increase in physical data rate. The analysis of the results reveals that explicit loss notifications and flow balancing are not sufficient to improve transport protocol performance in an IEEE 802.11n supported mesh backbone, rather a specific mechanism is required to synchronize the transport queue management with lower layer scheduling that depends on IEEE 802.11n features, like channel bonding and frame aggregation. The findings of this paper give the direction to design a new transport protocol that can utilize the full capacity of IEEE 802.11n mesh backbone.

1. Introduction

Wireless mesh network [1] is a backbone network of wireless routers that extends last mile broadband connectivity to the end users. Due to its deployment and management-friendly nature, mesh networks are gaining popularity for providing commercial broadband connectivity to the urban as well as rural areas. The IEEE has standardized mesh networking through the augmentations in well-established 802.11 standard, termed as IEEE 802.11s [2]. In a mesh network, mesh routers, also known as mesh stations (STAs), provide connectivity to the end-users and support multi-hop mesh forwarding. One or more of the mesh STAs, known as mesh gates, support gateway connectivity in the mesh backbone to bridge between the mesh network and the outside Internet.

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IEEE 802.11n [3] has been standardized in the last decade to support high data rate connectivity over the wireless media. 802.11n supports a number of enhancements to provide physical data rates up to 600 Mbps. First, it adopts the MIMO technology to improve the network capacity through spatial diversity and improved channel gain. Further, the physical layer supports channel bonding, also known as 20/40 connectivity, where two 20 MHz channels are combined to form a wider channel of 40 MHz. Channel bonding theoretically doubles the physical data rate [4], and therefore 40 MHz channel supports up to 600 Mbps, where 20 MHz provides a maximum data rate of 288 Mbps. It can be noted that current commercial implementations of IEEE 802.11n support 300 Mbps in 40 MHz channel, and 144 Mbps in 20 MHz channel.

802.11n also supports frame aggregation as the MAC layer enhancements [5] where multiple back-to-back MAC frames are transmitted simultaneously to reduce the channel access overhead due to collision. Two different forms of aggregation are proposed in 802.11n—MAC service data unit (MSDU) aggregation, known as A-MSDU, and MAC protocol data unit (MPDU) aggregation, known as A-MPDU. In case of A-MSDU, multiple upper layer data packets (MSDU) are combined at the MAC layer to form a single MAC frame. On the contrary, multiple MAC layer frames (MPDU) are combined to form a single frame with a common header, in case of the A-MPDU.

Due to the high data rate support, IEEE 802.11n can be used as an effective technology to provide broadband connectivity over a mesh network. It can be noted that IEEE 802.11n and IEEE 802.11s standards can coexist in a network, forming a high data rate IEEE 802.11n+s mesh network. Several existing works [4,6–12] in the literature have studied the performance of IEEE 802.11n from experimental, theoretical and simulation analysis. These works have revealed that, though 40 MHz channel supports better MAC performance, it is more error prone compared to the 20 MHz channel with identical antenna settings. However a major limitation of these works is that they have studied the performance over a point-to-point high data rate wireless link, whereas the performance issues are more critical over a mesh network. Further, except [4], all other works have analyzed IEEE 802.11n performance at the MAC layer. Though Deek et al. [4] have analyzed TCP performance over a point-to-point IEEE 802.11n network, they have considered the baseline TCP-Reno protocol only, and have not investigated the advanced transport protocol variants.

In this paper, we study the performance of transport layer protocols over a IEEE 802.11n+s mesh network, using results from a practical mesh testbed. This paper evaluates the performance of four transport protocol variants over high throughput wireless mesh networks, namely LT-TCP [13], TCP/NC [14], TCP-Horizon [15] and WCP [16]. The first two protocols are designed to handle random channel errors and data losses in wireless environment, whereas the last two protocols are developed specifically for multi-hop and mesh networks. The major contributions of this paper are as follows:

- End-to-end performance of a transport protocol like TCP has been thoroughly investigated through the results from a practical IEEE 802.11n+s mesh network. To the best of our knowledge, this is the first paper that reports transport protocol performance over a high speed mesh network, with the underlying 802.11n and 802.11s protocol stack.
- Our evaluation shows that WCP outperforms other transport protocol variants in most of the cases. However, WCP shows a negative impact at 40 MHz channel, with high data rates, where LT-TCP and TCP/NC performs better than WCP. We show that none of the existing transport layer protocols show consistent performance over high throughput mesh networks. The best transport protocol variant depend on underlying physical data rate selection.
- Nevertheless, our analysis shows that the end-to-end user-level goodput is typically at most one half of the maximum network capacity as indicated by Jun et al. [17]. Since WCP outperforms other protocol variants in most of the cases, we have selected WCP for a detailed performance evaluation with different data rates and physical layer aggregation level.
- We show that IEEE 802.11n channel bonding and frame aggregation sometimes result in negative impact over WCP (mainly with high data rates). In some scenarios, WCP performance drops with the increase in data rates. The performance anomaly of WCP at high data rates comes from correlated but bursty transport packet losses, as well as the failure of round trip time (RTT) estimation mechanisms. We show that RTT is a poor indicator of congestion in 40 MHz channel at high data rates.
- Our analysis reveals that A-MSDU aggregation performs better compared to A-MPDU aggregation, when transport protocol performance is concerned. This is in contrast to the existing concept that A-MPDU aggregation outperforms A-MSDU aggregation in lossy environments. The results from the testbed show that though individual MPDUs can be recovered from an A-MPDU during random channel errors, consecutive losses of a few MPDUs due to correlated channel errors affect the transport protocol performance.
- This paper shows the requirement of designing a new transport layer data rate adaptation protocol for high throughput mesh networks, that takes care of correlated and bursty losses as well as RTT fluctuation with high variance. Further, the flow balancing and unfairness issues over mesh networks need to be addressed. In this way, this paper opens several directions for future research on transport protocol design and adaptation over high throughput mesh networks.

The rest of the paper is organized as follows. Section 2 gives a brief survey of TCP like transport layer protocol details over wireless multi-hop and mesh networks, with a brief description and working procedure of the four protocol variants used in this paper for transport protocol performance evaluation. Section 3 describes the testbed setup with detailed methodologies adopted for protocol evaluation using testbed results. A comparison of the four protocol variants, namely LT-TCP, TCP/NC, TCP-Horizon and WCP, is reported in Section 4. The detailed performance evaluation and analysis of WCP protocol is described in Section 5. Finally, Section 6 concludes the paper.