Evaluation of Transport Layer Protocols over Wireless Multi-hop Networks

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Abstract- In a wireless multi-hop network (WMN), numerous QoS mechanisms such as routing, topology control protocol and transport layer protocols (TLPs) have been proposed. The focus of this study is on the TLPs. TLPs are responsible for connection establishment and attempt to ensure that all data are transmitted from source to target destination safely. Performance of Traditional TLP (such as TCP) deteriorates in WMNs. Traditional TLPs assume that all packets losses are due to network congestion, whereas the WMN can be greatly affected by other causes such link and route failure, route changes, and medium contention in a shared environment with an increasing network size. Several TLPs have been proposed to address this problem in the literature, but it is not clear which of these TLPs provide optimal performance over WMNs, since they are not compared in a consistent manner in previous works. As a result, we selected ten TLPs from literature. Using ns2 simulator, we evaluated and compared the performance of the selected TLPs. Based on the results obtained, recommendation on the design features for an ideal TLPs applicable to WMNs were also made.

Key terms-Transport layer protocols, Quality of services, recommendations

I. INTRODUCTION

A wireless multi-hop network (WMN) is a network of devices (nodes) which are connected by wireless links [1]. Each wireless link has a limited communication range and several pairs of nodes are unable to communicate directly, therefore, the nodes must send data to each other through one or more cooperating intermediate nodes. WMN is a promising technology for several interesting applications such as broadband home networking, community and neighborhood networks, coordinated management and intelligent transportation systems [17]. This technology is gaining significant attention as a feasible way for Internet service providers (ISPs) and other end-users to establish robust and reliable wireless broadband service access at a reasonable cost. Multiple mechanisms for quality of service (QoS) provisioning have been proposed for WMNs.

These mechanisms include transport layer protocol (TLP), routing protocol (RP), load balancing (LB), medium access control (MAC) and topology control (TC) [2], [3]. The research community has pointed out that the traditional TLPs (TCP) behavior in WMNs is far from meeting the QoS requirement for WMNs [5], [4]. One of the reasons identified is that WMNs have unique characteristics when compared to other networks (such as wired networks) [5]. TCP assumes that all packet losses are due to network congestion which is not the case in WMNs [5], [6]. It has been proven that in WMNs packet losses are due to other reasons such as high bit error rate, medium contention, route or link breakage, and radio channel errors [6],[7],[8],[9]. A significant number of new TLPs have been proposed to improve the performance of traditional TLP over WMNs.

TLPs are classified into four categories namely: TCP variants (TCP-Vs), UDP variants (UDP-Vs), Hybrid TLPs (HTs) and Entirely new TLPs (ENTs) [16][29]. TCP-Vs and UDP-Vs are the extensions of TCP and UDP, respectively. TCP-Vs were proposed to enhance the TCP performance in wireless environments. UDP-Vs are the enhanced versions of UDP. In real-time delivery UDP instead of TCP is usually applied as a TLP [17], [19].

TCP performance degrades in real time applications, and hence UDP was developed for real-time applications [16]. HTs are a combination of TCP and UDP based protocols. In WMNs, a number of clients can generate TCP and UDP traffic which goes in the multi-hop path from one node edge to another node edge or node to gateway node [10]. Therefore, improving only the performance of TCP protocol may not improve the overall performance of the WMNs (10). As a result, the HTs were developed.

ENTs are protocols designed to avoid fundamental problems of TCP and UDP [16]. These protocols were developed to tailor to the characteristics of WMNs. The TLPs of the four identified categories of TLPs are not compared in a consistent manner. Thus, it is not clear which TLP yields the optimal performance over WMNs. From the best of our knowledge, the comparison is among two to four TLPs in most cases, not more than five TLPs.

As a result, we selected two protocols from each of the four categories for performance evaluation and comparisons. Our comparisons also include traditional TLPs as the basis of our study, therefore, we considered ten TLPs in our comparison. In order to identify an optimal TLP applicable to WMNs, we evaluated and compared the performance of these ten selected TLPs using network simulation tool (NS2). Based on the results obtained, the TLP which most suitable for WMNs was identified and recommendations for the design features for an ideal TLP applicable to WMNs was made.

The remainder of this paper is organized as follows. Section II presents a summary of related work while Section III describes the research trends for TLPs. In Section IV, we presented performance evaluations for TLPs applicable to WMNs. The performance summary and recommendations for design features for an ideal TLP applicable to WMNs are given in Section V. Finally, Section VI concludes this paper with possible future research directions.

II. LITERATURE REVIEW

Traditional TLP (TCP) misinterprets route or link failures, medium contention, and high bit errors as congestion and invokes congestion control (CC) mechanisms which result in unnecessary retransmissions and loss of throughput.

As result, Chandran in [20] proposed a TCP-FEEDBACK (TCP-F) scheme whereby the traffic in source distinguishes between router or link failures and network congestion losses. This scheme has been compared with TCP only through NS2 simulations. Explicit Link Failure Notification (ELFN) [21] uses feedback notification as TCP-F but in ELFN the feedback come from lower layers to notify TCP explicit about link failures. Comparison of this scheme with other TCP-Vs such as TCP-Reno, TCP-Vegas as well TCP was done using NS2 as TCP-F. This indicates that less than five TLPs were being compared.

In [4] out-of-order packet lost detection was sufficient to indicate packets lost due to link or route failures instead of notifications used in TCP-F and ELFN. TCP suffers from multimedia applications such as video and audio streaming over WMNs, as result, UDP-Vs were proposed. In [30] TFRC attempts to faithfully match the throughput of TCP, but it suffers the same efficiency problem of moderate to high random errors [6]. Thus, TFRC was extended to suit the characteristics of WMNs.

Among the TFRC extensions there is TFRC Wireless [22] and MULTFRC [5]. In particular, video transport protocol (VTP) [6] has been proposed and presented. The comparison of TVP and the TFRC extensions was performed in [6]. In [23], IHCC was proposed; it is designed to work with both TCP and UDP traffic over WMNs. The IHCC has the lightweight error detection and correction mechanisms which guarantee a fast reaction to changing medium conditions and slow overhead. This TLP has been compared to traditional TLPs and ADTCP [25].

A good fairness properties and throughput were observed using NS2. As solutions for wireless networks emerge, the problem related to specific type of networks came into play. Lui and Singh in [24] proposed ATCP as TCP performance suffer from high bit errors and frequent route changes in wireless ad hoc network. ATCP does not impose changes to TCP itself, but it implements an intermediate layer between the network and transport layers.

This scheme relies on the ICMP and ECN schemes to detect network partition and congestion, respectively. Several TLPs such as TCP-EXACT and UDP-EXACT [22] from different categories designed to provide solution similar to ATCP, but they are not compared in a consistent way and the comparisons in most case are between two to three TLPs, no comparisons between up ten TLPs. There are many TLPs reviewed but due to space limitations the summary of the TLPs can be found in Table 1. The full meanings of the words abbreviated in this table are as follow: Real-Time Transfer (RTT), Cross-layer Aware (CLA), Test-beds (TBs), and QoS-Aware (QoS-A).

Table 1: Transport Layer Protocols

Group	Protocol	RTT	CLA	TBs	NS-2	QoS-A
TCP-V	I-TCP	×	×	×	√	×
	M-TCP	×	×	×	√	×
	WTCP	×	×	×	√	√
	TCP-F	×	×	×	√	×
	SNOOP	×	×	×	√	×
	ST-PD TCP	×	×	×	√	×
	TCP Door	×	×	×	√	×
	EXACT	×	×	×	√	√
	TCP-AP	×	×	×	√	√
UDP Variant	RAP	√	×	×	√	×
	TFRC	√	×	×	√	√
	ARC	√	×	×	√	×
	DCCP	√	×	×	√	√
	LATP	√	√	×	√	√
	HERC	√	×	×	√	×
Hybrid	LLE-TCP	√	√	√	√	√
	LLAP	√	√	×	√	√
	IHCC	√	√	√	√	√
Entirely New	WXCP	×	×	×	√	√
	ATP	×	×	×	√	√
	AR-TP	×	√	×	√	√
	ATP	×	×	×	√	×

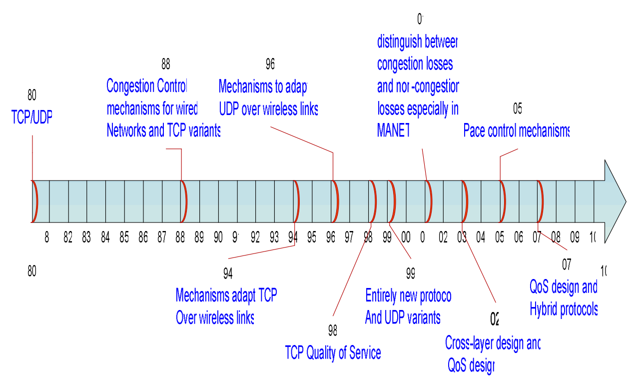

Figure 1: Research Trends for WMNs

III. RESEARCH TRENDS IN TLPS APPLICABLE TO WMNS

The research trends for this study are given in a pictorial form in Figure 1. The trends indicate the focus of the research community concerning TLPs from 1980 up to 2011. This research trend clearly indicates what problem was being solved using TLP in the particular year. Our trends start from the wired technology until the wireless technology come into play. The first TLP (TCP) came into play as the network congestion caused the poor performance of the network as a whole. Such situation occurred on the early Internet (wired network) and lead to the development of the TCP with congestion control (CC) mechanism. Initially TCP was for wired network where congestion is a regular cause for packet loss [8]. As much as TCP provides the CC mechanisms for wired network but it was not suitable for real time applications.

Therefore, the issue of UDP came into consideration to set TCP free from real-time applications problems associated with audio and video streaming [28]. As from 1988, TCP was being upgraded, different version of TCP using various approaches such as Slow Start and

Congestion Avoidance [26], Fast Retransmit and Fast Recovery [27] were proposed to minimize the network congestion. Many TLPs were designed to extend TCP (TCP related) in order to increase the degree of CC. Similarly, UDP related transport layer protocols were also developed to solve the UDP-specific problems on wired networks. During the 1990s the issue of wireless technology started as far as the TLPs are concerned. When the wireless technology comes into play, the traditional TLPs (TCP and UDP) were adopted in the wireless network environment. The traditional TLPs performed poorly in wireless environments. TCP assumes that all packet losses taking place in any network are due to network congestion [25], [26].

Therefore, the traditional TLPs were extended to solve the problems experienced by traditional TLPs in wireless environments. In the late 1990’s and early 2000’s, the focus of researchers shifts from network congestion to the issue of Quality of Service (QoS). In the mid 2000's the issue of cross-layer came into play. At the moment the optimization of the cross-layer optimization is an open research issues. These trends indicate the state-of-art for TLPs. This trend enabled us to easily identify the TLPs for performance evaluations together with literature analysis in Table 1.

IV. PERFORMANCE EVALUATION

In this section, we present the results of the simulation-based performance comparisons of the TLPs to find the most suitable TLP over WMNs.

4.1. Simulation Details

The results of the simulation-based performance evaluations of the QoS mechanisms for TLPs associated with WMNs. We compare the ten TLPs based on the following QoS performance metrics: throughput, delay, packet delivery rate, and packet retransmissions. The simulations were performed using static nodes. HWMP was used, a newly produced routing protocol standard for Wireless Mesh Networks (one of the three types of wireless multi-hop networks. Wireless mesh network is more static. Therefore, since our evaluations are based on a static wireless networks we considered HWMP as the most reliable routing protocol for our experiments. The rest of the simulation parameters can be found in Table 2. Network was assumed to always have data to send from source to destination with an aid of TLPs.

Table 2: Simulation Parameters

Protocols	**TLPs**
Simulation Time	100s
Number of Nodes	20- 200 nodes
Map Size	2500x1500
Speed	0.0 per second
Mobility Model	Stationary
Traffic Type	Both cbr and tcp
Packet size	512 byte
Connection Rate	4.0
MAC protocol	IEEE 802.11 DCF
Routing protocol	HWMP
Propagation model	Two ray ground
Antanna	Omni-directional
Channel capacity	2
Transmission range	250m

4.2. Evaluation Results

In this section, we describe and analyses the results. We considered throughput, delay, packet delivery ratio, packet retransmission against network size. The results and results analysis can be found in subsection a, b, c, and d, respectively.

A. Throughput

The purpose of this experiment was to determine the average rate of successful data packets delivery over the network communication channel. Results highlighted in Figure 2 show that traditional TLPs produced less throughput than all other TLP categories. The traditional TLPs treat all packet losses as congestion losses [7], [11], while in WMNs packet losses are mainly owing to the link or route failures[5][6][20].

Time-sensitive UDP-Vs (LATP and HERC), achieve less throughput than all TLP categories but not traditional TLPs. The poor performance by UDP-Vs applicable to WMNs results from the fact that TLP are not reliable and do not consist of CC mechanisms [31][22]. LATP outperforms HERC, since the LATP provides a rate control mechanisms for media streaming applications in contention based WMNs.

As shown in Figure 2, TCP-Vs (Snoop and TCP-AP) with the ability to differentiate between congestion and non-congestion losses outperforms traditional and UDP-Vs. Among the two TCP-Vs TLPs, TCP-AP fares far better throughput than Snoop as the TCP-AP has an adaptive pacing mechanisms to control the level of data offered into the network. Entirely new TLPs (ENTs) have better throughput than all TLP categories but not HTs. The ability of ENTs to decouple congestions and reliability mechanisms makes these TLPs to yield better performance when

applicable to WMNs. HTs (LLAP and LLE-TCP), outperform all other types of TLPs considered in this study. Both HTs used cross-layer approach and they improve TCP performance over WMNs. HTs are capable to work with both real time and non-real time applications. Results in Figure 2 indicate that for all TLPs, the performance decreases as the network size increases.

B. Delay

The purpose of this experiment was to determine the average time taken to deliver the application layer data packets from the source to intended destination. The results of this experiment were plotted in Figure 3.In this result, traditional TLPs (i.e. TCP and UDP) experienced more delay. Delay-tolerant TCP experienced more delay than delay-sensitive UDP. TCP attempts to ensure reliability through packet retransmission, as results, more delay experienced by TCP. UDP-Vs (UDP variants) experience less delay than traditional TLP as well as TCP-Vs (TCP variants). This is simple because UDP-Vs are highly intolerant of delay. TCP-Vs have to wait for acknowledgements before sending another packet. On the other hand, TCP and TCP-Vs attempt to impose reliability

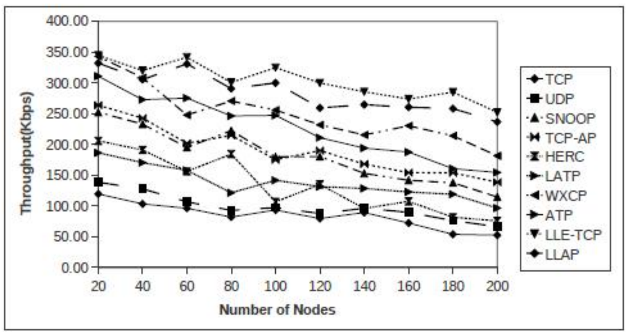

Figure 2: Throughput versus number of nodes

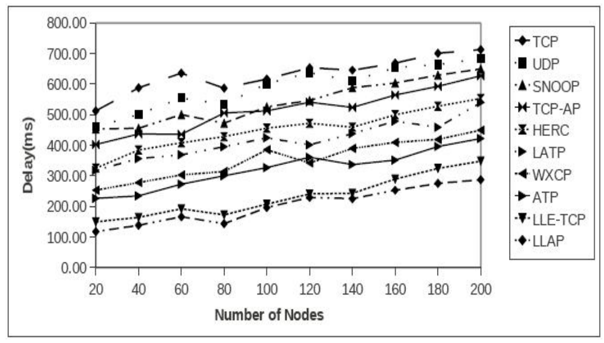

Figure 3: Delay versus number of nodes

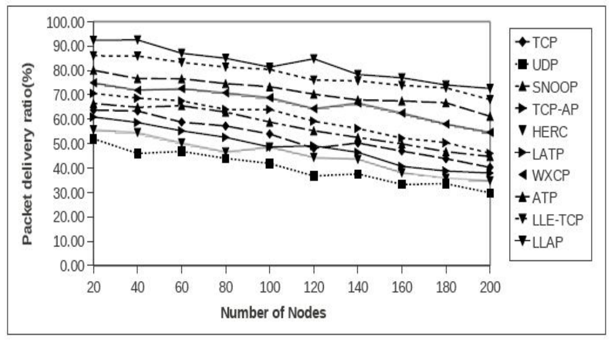

Figure 4: Packet delivery ratio versus number nodes

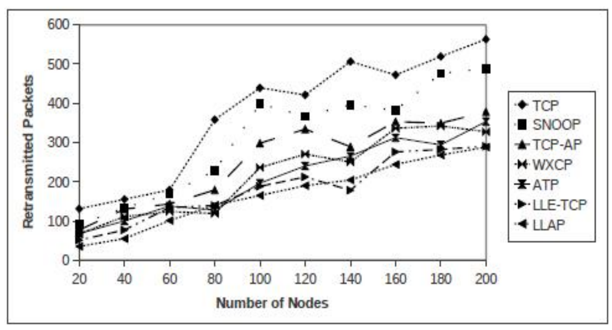

Figure 5: Number of PR versus number of nodes

through packet retransmission, therefore, increasing delay. TCP-Vs have far better performance than the classical TCP. However, Snoop (TCP-V) has more delay than TCP-AP because TCP-AP implements rate based scheduling of transmission within the TCP congestion window. The ENTs (WXCP and ATP), achieve better performance in terms of delay than TCP-Vs and UDP-Vs. This is due to the fact that ENTs were specially crafted for WMNs. HTs (LLE-TCP and LLAP), experienced less delay than all other TLPs. These TLPs work well with both real time and non-real time applications. The sophisticated adaptive pacing mechanisms enable the HTs to reduce delay in WMNs. For all TLPs, the delay increases proportionally to network.

C. Packet delivery Rate (PDR)

The intention of this experiment was to determine the network's ability to successfully deliver data packets to the destination. A PDR of 0% represents the total failure of the network to deliver data packets whilst the PDR of 100% shows successful delivery of all the packets.

Figure 4 graphically depicts the ratio at which TLPs deliver packet against the network size when they are applied to WMNs. UDP and it variants have a very low PDR compare to all TLPs applicable to WMNs. UDP and UDP-Vs (delay-sensitive) without CC mechanisms, they are mostly concerned in reducing delay not reliability.

The TCP and TCP-Vs (interested in reliability), they attempt to ensure that the packet is delivered as they retransmit the packet when the sender does not receive the delivery notification from the receiver. As a result, the PDR achieved in TCP and TCP variance is higher. The ENTs have good PDR, these TLPs consist of the mechanisms to control the packets transmission rate as well as the sophisticated congestion control (CC) techniques and reliability mechanisms. These mechanisms secure the packet from the source to the target destination, thus, the PDR increases. HTs, supporting transmission of data packet for both real time and non-real time applications and they have mechanisms to adaptively control the load offered into network, reported the best PDR than all categories. Figure 4 shows that Hybrid's PDR is between 70% and 95%. The results suggest that TLPs with less delay they have better throughput as well as PDR.

D. Packet retransmission (PR)

The main purpose for this experiment was to determine how the number of packet retransmission affects the performance of the TLPs. Packet retransmissions (PRs) should occur when it is certain that a packet to be retransmitted was actually lost [14]. The CC mechanisms assist in reducing the number of packet retransmissions, thus, the number of PR is considered to indicate the degree of network congestion experienced by WMNs when the selected TLPs applied to it.

On the other hand, PR was considered in this study since it indicates how reliable these TLPs are over WMNs. Figure 5 depicts the results highlight for packet delivery ratio against the network size for TLPs over WMNs. UDP and UDP-Vs are not considered in this experiment since they do not contain PR mechanisms. The results reported in Figure 5 depict that for all TLPs the numbers of PRs increase as the network size increases. In WMNs, TCP experiences more packet delivery errors, since it was designed without taking into consideration the characteristics of wireless networks. As a result, TCP experienced a large number of PRs compare to TCP-Vs. Snoop experienced more PRs than TCP-AP. Snoop experiences more PRs than TCP-AP. A better performance by TCP-AP results from the fact that, TCP-AP sends packets at a pre-determined rate. It sends new packets into the network only when the old packet delivery has been acknowledged. ENTs experience less PR than all TLP but not hybrid. These ENTs can precisely estimate the congestion conditions. This reduces network congestion which can lead to increase of PRs. An ATP (ENT) has less number of PRs than WXCP because it consists of rate based transmission with quick-start during connection initiation and route switching congestion detection. An adaptively estimation of four hop detection (FHD) on the path and transmission of the packets with estimated FHD interval allow the HTs to reduce the number of PRs to lesser than all other TLPs considered.

V. Performance Summary

Figure 6 summarizes the performance of TLPs over WMNs. Ratings are ranging from ‘1’ to ‘10’, with “1” representing the best performing TLP and ‘10’ representing worst performing TLP. The meanings of the words in Figure 6 are as follow: T- Throughput versus network size, D- Delay versus network size, PDR- Packet Drop Ratio versus network size, and PR- Packet Retransmission against network size. The experiments reported in section 3 as well as the concise summary provided in Figure 6, enabled us to easily determine an optimal performing TLP (LLAP) over WMNs. While looking for the optimal performing TLP applicable to WMNs, we automatically identified the optimal performing TLP category as well. The optimal performing category according to our study is HT category. From this study, it is possible to determine the best performing TLP per category. The second best performing category is the ENT, it outperform hybrid in some instances. The ENTs are followed by the TCP-Vs. The worst performing TLPs are the UDP-Vs.

Figure 6: Performance Summary

Group	TLPs	T	D	PDR	PR
HTs	LLAP	1	1	1	1
	LLE-TCP	2	2	2	2
ENTs	WXCP	3	4	4	4
	ATP	4	3	3	3
TCP-Vs	SNOOP	5	6	6	6
	TCP_AP	6	5	5	5
UDP-Vs	LATP	7	7	8	
	HERC	8	8	9	
Traditional	UDP	9	9	10	
	TCP	10	10	7	7

5.1. Recommendations

Based on the results obtained, we managed to make recommendations for an ideal TLP applicable to WMNs. These recommendations should be taken into considerations by any one who would like to develop a TLP applicable to WMNs. The recommendations are as follows.

1. The use of CC algorithms: From our results, it is clear that TLPs with an advanced CC mechanism yield excellent throughput, less delay and less PDR. CC mechanisms reduce packet loss rate and packet retransmissions. TCP had more retransmission because it cannot distinguish between the congestion loss and non-congestion loss. We, conclude that sophisticated congestion mechanisms are crucial requirements for optimal TLP performance. Several CC schemes that have been designed already for different types of networks and from different perspective such as cross-layer, QoS aware of recent, but still to the best of our knowledge, there is no CC algorithm designed to cater for all this congestion schemes combined into one which can be applied to any network scenario to control and avoid network congestion. Therefore, the study to combine several congestion into one (One fits all CC scheme) scheme is important.

2. TLPs should be cross-layer aware: All the cross-layer aware TLPs outperform all the TLPs which are not cross-layer aware this is because transmission of data packet does not involve TLPs only. The process includes many other protocols e.g. routing protocol which are found in other layers. The cross-layer aware TLPs (such as LLE-TCP and LLAP) outperform the non cross-layer aware TLPs in all aspects that were considered in this research. Although cross-layer aware TLPs perform better based on the study, but cooperative Load and Traffic Managing process is needed. Thus cross-layer optimization (CLO) can be used to provide cooperative management, where Load and Traffic managing processes can be made possible using interface between cross-layer optimization entity and the management in the application, transport and network layer stacks.

3. TLPs should be application independent: The HTs outperformed all other TLP categories in all aspects. These transport layer protocols work well with both real time and non-real time applications. A good TLP is the one which is applicable to any type of applications i.e. it should not be application specific.

4. Quality of Service (QoS) aware: Taking from the results we reported above, QoS is still an issue.

There are TLPs which are QoS aware, but their performance still needs to be improved especially the TCP and UDP-Vs. This is due to problems such as medium contention, temporary link failure, frequently route changes, and etc. The HTs have better degree of user satisfaction. The problem with TLPs as far as QoS is concern is that, they do not synchronizes read of QoS loading at each layer i.e. mating cross-layer and QoS provisioning processes. As load shift/reallocate, increase or decrease, and when problems occurs, some adjustments are important due to the fact that the process such network delay statistics, existing source-receiver (transmission) relationship and the statistics regarding allocating source to receiver may require some QoS aware adjustments.

5. Scalability: The performance of all TLP degrades as the networks increase. Even the HTs which we were found to be the best also experienced the same problem. All these conditions confirm that the issue of network scalability still needs attention. The fact we have identified that network scalability requires attention does not mean scalable network does not have any problem. In a large geographical area, thus the long distance can incur some network delays while trying to provide network scalability. Therefore, delay intolerant applications can be affected even if the network is scalable. As results we recommend anyone who will be interested to inflict a scalable TLP should make it a point that it is an anti-delay scalable TLP applicable to WMNs.

6. TLPs should be distance tolerant: The performance of all TLPs mortifies as the distance between the nodes increases. The HTs which performed better in many cases but they are even outperformed by ENTs and one of the TCP-Vs (i.e. TCP-AP) when throughput, packet retransmission and packet delivery ratio versus distance between nodes were concerned.

VI. CONCLUSION AND FUTURE WORK

This paper presents a comparison of the existing TLPs applicable to WMNs. The purpose was to determine an optimal performing TLP. We conducted experiments in ns2 simulator. Ten TLPs, two from each category were simulated and analyzed their performance.

The hybrid protocols which are comfortable to work with both real-time and non-real time applications, cross-layer aware, QoS aware and with sophisticated adaptive pacing mechanisms found to be optimal performing protocols over WMNs. The recommendations of the features for an ideal TLP applicable to WMNs were produced based on the results analysis. The NS2 is the only simulation tool considered in our study; therefore, in future we would consider the use of Testbed as the evaluation tool.

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