Macrothink Institute™

Network Protocols and Algorithms
ISSN 1943-3581
2015, Vol.7, No.2

TCP-AP Enhanced Behaviour With rt-Winf And Node Count: boosted-TCP-AP

Luís Barreto
Escola Superior de Ciências Empresariais, Instituto Politécnico de Viana do Castelo, Portugal
Tel: +351258809679 E-mail: lbarreto@esce.ipvc.pt

Received: May 25, 2015 Accepted: July 25, 2015 Published: July 31, 2015

DOI:10.5296/npa.v7i2.7677 URL: http://dx.doi.org/10.5296/npa.v7i2.7677

Abstract

Congestion control in wireless networks is strongly dependent on the dynamics and instability of wireless links. Therefore, it is very difficult to accurately evaluate the characteristics of the wireless links. It is known that TCP experiences serious performance degradation problems in wireless networks. New congestion control mechanisms, such as TCP-AP, do not evaluate accurately the capacity and available link bandwidth in wireless networks. In this paper we propose new congestion control protocol for wireless networks, based in TCP-AP. We name the protocol boosted-TCP-AP. It relies on the MAC layer information gathered by a new method to accurately estimate the available bandwidth and the path capacity over a wireless network path (rt-Winf), and also takes into consideration the node path count. The new congestion control mechanism is evaluated in different scenarios in wireless mesh and ad-hoc networks, and compared against several new approaches for wireless congestion control. It is shown that boosted-TCP-AP outperforms the base TCP-AP, showing its stable behavior and better channel utilization.

Keywords: Available Bandwidth, Congestion Control, Measurements, Path Capacity, Performance, Wireless Networks.

1 Introduction

New technology developments and more needs in terms of mobility communications has led to a significant increase in the use of wireless networks. Wireless networks are being installed everywhere, it is possible to find them in airports, public services buildings, restaurants and also freely available in some communities or neighborhoods. Wireless networks are being used for sending messages, for videoconferencing and for high performance multimedia streaming applications. All these applications have different needs in terms of performance, congestion control and network quality. Wireless networks uses the air as the access media, this is a shared medium more sensitive to interferences and congestions. High performance applications suffer, when a wireless network is densely populated, of severe performance reduction that results in quality degradation and unhappy users.

The Transmission Control Protocol (TCP) [1] is the most used congestion control protocol in wired and wireless networks. The congestion control techniques of TCP are proven to be effective in the group of Internet wired networks. But, this is not true in wireless networks, where packet loss or/and delay can result due to congestion and due to time varying nature of the wireless channel. Hence, applying the congestion control of wired networks directly in wireless networks may not be suitable. In wireless networks, TCP performance suffers for a variety of reasons. For example, TCP cannot distinguish random wireless losses from congestion. The most used solution, using TCP in traditional wireless networks, is to divide the TCP connection at the base station into two separate connections, one for wireless and one for wired. When using multi-hop wireless ad hoc networks, with high mobility TCP can interact negatively with the network layer and force unnecessary route changes. This causes unnecessary TCP retransmissions.

Wireless networks have also other factors that limit their performance, this factors as stated in [2] are the limited capacity and available bandwidth. This results, also, in severe congestion collapses. A congestion control scheme which provides an efficient and accurate sharing of the underlying network capacity among multiple competing applications is crucial to the efficiency and stability of wireless networks. Actively using link capacity and available bandwidth for congestion control will surely make these networks more efficient. Link capacity can vary due to a variety of factors, such as handoffs, channel allocation and, of course, channel quality. [3] presents a new mechanism for measuring wireless link capacity and available bandwidth, called rt-Winf. rt-Winf uses the information already present in the network and available at the MAC layer. Another important characteristic of rt-Winf is that it can be used by any existing wireless equipment.

To address the congestion control problems of wireless networks, new congestion control techniques have been proposed. TCP with Adaptive Pacing (TCP-AP) [4] is a recent congestion control mechanism, specifically designed for multi-hop wireless networks, it uses a 4-hop propagation delay technique. TCP-AP uses a hybrid scheme between a pure rate-based transmission control and TCP's use of the congestion window. However, TCP-AP as studied in [5] is very conservative and is not using efficiently the medium. TCP-AP relies only on the 4-hop propagation delay to evaluate link available bandwidth and capacity, thus, not taking into consideration all the factors that influence link evaluation.

This paper proposes the integration of rt-Winf with TCP-AP through a cross layer approach, the consideration of the nodes along a path and, already integrated in rt-Winf, the collision probability. The new protocol is called TCP-AP with rt-Winf. This improved capacity and available bandwidth evaluation integrated in TCP-AP will significantly improve the performance as compared to base TCP-AP, as it is shown through the obtained simulation results, on both ad hoc and mesh networks. In terms of wireless networks congestion control and behavior it represents a significant step towards their knowledge, showing that cross-layer information can improve the network performance.

The remaining of this paper is organized as follows. Next section, section 2, briefly presents the related work on congestion control mechanisms for wireless networks. Then, section 3 describes how *rt-Winf* is integrated with TCP-AP, and how node path count can be included in these approaches. Section 4 describes and discusses the results obtained through simulation, using mesh and ad-hoc scenarios with different characteristics. Finally, section 5 presents the conclusions and future work.

2 Related Work

New efforts have been made to improve congestion control in wireless networks. The Wireless Control Protocol (WCP) [6], Wireless Control Protocol with Capacity Estimation (WCP-Cap) [6], Cooperative Neighborhood Airtime-limiting (CNA) [7], Wireless Transport Protocol That Uses Reliable Per-Hop Block Transfer as a Building Block (HOP) [8], the Distributed Flow-Control Mechanism That Solves The Turbulent Behavior of IEEE 802.11 (EZ-Flow) [9] and Neighborhood Random Early Detection (NRED) [10] are some examples. TCP, as the most used congestion control protocol, has also been the underlying developments for some congestion mechanisms in wireless environments, TCP-AP [4] is one example. More recent developments, like the eXplicit Congestion control Protocol-blind (XCP-b) [11], the eXplicit Congestion control Protocol with Real Time Wireless Inference Mechanism (XCP-Winf) [12] and the Rate Control Protocol with Real Time Wireless Inference Mechanism (RCP-Winf) [12], are based on rate based congestion protocols like the eXtensible Control Protocol (XCP) [13] and the Rate Control Protocol (RCP) [14].

WCP is an Additive-Increase/Multiplicative-Decrease (AIMD) based rate-control protocol for multi-hop wireless networks. WCP was designed with the goal to be used on networks with arbitrary traffic pattern. During congestion, WCP signals all flows in a neighborhood of congestion and sets the control interval to the maximum Round Trip Time (RTT) of any flow in the neighborhood. WCP explicitly exchanges congestion information within a neighborhood, and all nodes within the neighborhood mark packets with congestion indicators, triggering rate reductions at the source.

WCPCap is a distributed rate controller that estimates the available capacity within each neighborhood, and divides this capacity to contending flows. With WCPCap it is evident that considering wireless congestion collectively over a neighborhood of a link is essential to any future design of wireless congestion control. WCPCap uses a sophisticated stochastic model for estimating the achievable rate region, given packet loss rates, topology, and flow information. It then allocates the achievable capacity fairly across flows, sending feedback to the sources.

CNA is a hybrid approach, in that it explicitly allocates the channel resources, but provides only imprecise feedback to the source. CNA achieves efficient airtime allocation by distributing available airtime within a wireless neighborhood, then monitoring the air utilization and dynamically redistributing unused airtime to improve overall airtime usage. The authors of CAN claim that it achieves transparency, low overhead, and responsiveness. CNA considers airtime to be the fraction of the time that a wireless link can occupy the shared channel; it does not consider the time a node is waiting to transmit.

HOP is a clean-slate design of hop-by-hop congestion control. HOP tries to use reliable per-hop block transfer as a building block. Hop is referred by its authors as: fast, because it eliminates many sources of overhead as well as noisy end-to-end rate control; robust to partitions and route changes, because of hop-by-hop control as well as in-network caching, and simple, because it obviates complex end-to-end rate control as well as complex interactions between the transport and link layers.

EZ-Flow is a backpressure congestion control mechanism which does not require explicit signaling. A back-pressure mechanisms flow control allows loss-free transmission by having gateways verify that the next gateway has sufficient buffer space available before sending data, thus EZ-Flow is a cooperative congestion control. EZ-flow operates by adapting the minimum congestion window parameter at each relay node, based on an estimation of the buffer occupancy at its successor node in the mesh.

NRED identifies a subset of flows which share channel capacity with flows passing through a congested node. But, it identifies only a subset of contending flows: it misses flows that traverse two hop neighbors of a node without traversing its one hop neighbors. Moreover, the mechanism to regulate the traffic rates on these flows is quite a bit complex (it involves estimating a neighborhood queue size and using RED-style marking on packets in this queue). NRED has an important disadvantage of being is intimately tied to a particular queue management technique (RED) and requires special hardware for channel monitoring.

TCP-AP uses a 4-hop propagation delay technique, it considers a hybrid scheme between a pure rate-based transmission control and TCPs use of the congestion window to trigger new data packets to be sent into the network. A TCP sender adaptively sets its transmission rate using an estimate of the current 4-hop propagation delay and the coefficient of variation of recently measured round-trip times. The 4-hop propagation delay describes the time elapsed between transmitting a TCP packet by the TCP source node and receiving the packet at the node which lies 4 hops apart from the source node along the path to the destination.

XCP-Winf and RCP-Winf are two new congestion control mechanisms, which use MAC layer information through a cross layer communication process. The rt-Winf algorithm performs link capacity and available bandwidth calculations without interfering in the network dynamic, and without increasing network overhead, these parameters are then passed to the congestion control mechanisms based on explicit congestion notifications, XCP and RCP, to accurately determine the network status and act accordingly. The evaluation results of XCP-Winf and RCP-Winf, obtained through ns2 [15] simulations, show that the rt-Winf algorithm improves significantly XCP and RCP behavior making them more efficient and stable.

XCP-b is also a XCP based congestion control mechanism, it tries to extend XCP for shared-access, multi-rate wireless networks by calculating, using very complex heuristics, the available bandwidth of the wireless channel. XCP-b uses indirect parameters such as queue sizes and number of link layer retransmissions to obtain the desired measurements. XCP-b major drawback is that it becomes inefficient over highly dynamic wireless networks. In wireless environments with few nodes and less mobility, XCP-b outperform other wireless transmission protocols in terms of stability, fairness, and convergence.

Table 1 qualitatively compares the previous referred mechanisms along some dimensions. It is also included boosted-TCP-AP, for comparison purposes. It is important to reference that boosted-TCP-AP will use cross layer and rate information to allow a better congestion window use.

3 *boosted-TCP-AP* - Enhanced TCP-AP Behaviour

TCP-AP enhanced behaviour (*boosted-TCP-AP*) relies on the main functioning principles of TCP-AP, but uses information provided by rt-Winf [3] to determine the link capacity and available bandwidth, and overcomes the problem of the 4-hop propagation delay with the inclusion of node path count. As rt-Winf obtains the link capacity and available bandwidth in the

	Cross-Layer	Cont. Param.	cwnd/rate limit	Mult. Metrics	Med. Over-hearing	Inter. Node Feedback	MAC Multi Rate
NRED	Yes	Window			Yes		
XCP-Winf RCP-Winf	Yes	Rate	Yes	Yes	Yes	Yes	Yes
WCP		Rate	Yes			Yes	
WCPap		Rate	Yes			Yes	
CNA		AirTime				Yes	Yes
EZ-Flow	Yes	Buffer				Yes	
HOP		Window	Yes		Yes		Yes
TCP-AP		Window	Yes				Yes
XCP-b		Rate	Buffer				
boosted-TCP-AP	Yes	Rate	Yes	Yes			Yes

Table 1: Congestion Control Mechanisms Comparison.

MAC layer this information has to be accessed bay TCP-AP through a cross layer communication process. On example of such cross layer communication process is the MobileMan [16] cross-layered network stack. This communication system uses a shared database architecture, with a set of methods to get/insert information from/in the database accessible by all protocol layers.

Compared to the base TCP-AP, *boosted-TCP-AP* only changes the way each node calculates the four hop delay (FHD) and the average packet queuing delay per node (t_q), with the rt-Winf link capacity and available bandwidth values. Thus,

$$t_q = \frac{1}{2}(\frac{T_{RTT}}{h} - \frac{S_{data} - S_{ack}}{C_{Winf}}) \tag{1}$$

where T_{RTT} represents the RTT value, h represents the number of hops between sender and receiver, S_{data} is de size of the data packet and S_{ack} the size of the ACK packet. Finally, C_{Winf} corresponds to the link capacity obtained with rt-Winf. The previous equation allows to update the four hop delay by:

$$FHD = 4 \times (t_q + \frac{S_{data}}{AB_{Winf}}) \tag{2}$$

where AB_{Winf} is the rt-Winf available bandwidth.

As the standard TCP-AP, considers for its capacity and available band-width estimations within the 4-hop propagation delay, this technique is not very accurate, specially when dealing with high density and mobility scenarios, and due to the shared nature of the wireless medium, nodes along a multi-hop path (NP) contend among themselves for access to the medium. Thus, considering only 4-hop neighbourhood for the estimations is introducing inaccuracy. The available bandwidth and capacity estimation must, then, consider the nodes along the path between the source and the sink, that is, the contending successors and predecessors on the route path. Therefore to eliminate this in-accuracy, we changed *boosted-TCP-AP* with rt-Winf to use a coefficient (R is the unused bandwidth), that represents the proportion of bandwidth contention among other nodes on the path, thus, maximizing the throughput while guaranteeing fairness. If we consider NP as all nodes along the path and if $NP-1$ is equal or less than 4, then TCP-AP with rt-Winf is kept unchanged, if $NP-1$ is higher than 4 then the FHD equation, now called the hop delay (HD) is updated to:

$$HD = FHD \times R \tag{3}$$

where

$$R = 1 + \frac{1}{NP} \tag{4}$$

then,

$$HD = 4 \times (\frac{NP+1}{NP}) \times (t_q + \frac{S_{data}}{AB_{Winf}}) \tag{5}$$

Algorithm 1 shows the pseudo-code of an *boosted-TCP-AP* source node.

Algorithm 1: boosted-TCP-AP Source Node Operations.

```
foreach ACK packet do
    Node estimates node path (NP) from MAC ACK
    Node computes NP-1
    if $NP - 1 <= 4$ then
        $HD = FHD$;
    else
        $R = \frac{NP+1}{NP}$;
        $HD = R \times FHD$
```

Considering that a high density and high mobility network suffers from a great number of collisions, the rt-Winf mechanism it was also updated with the effect of collision probability. As rt-Winf works on the IEEE 802.11 [17] MAC layer that uses the Distribution Coordination Function (DCF) as the access method. This function is based on the CSMA-CA principle in which a host wishing to transmit senses the channel, waits for a period of time and then transmits if the medium is still free. If the packet is correctly received, the receiving host sends an ACK frame after another fixed period of time. If the ACK frame is not received by the sending host, a collision is assumed to have occurred. So, to improve efficiency and reliability of *boosted-TCP-AP* collision probability is accounted. When a sender cannot transmit due to collision, the backoff mechanism is activated. This mechanism is also consuming bandwidth. This bandwidth, C_{extra}, is defined by:

$$C_{extra} = \frac{T_{DIFS}}{T_{backoff}} T_m \tag{6}$$

, where T_{DIFS} is the IEEE 802.11 DCF Interframe Space, $T_{backoff}$ is the medium backoff time and T_m is the time between the transmission of two packets. The collision probability (P_c)

can then be defined as $1 - C_{extra}$. Applying this result to the rt-winf inference mechanism, the available bandwidth (AB) becomes:

$$AB = P_c \times AB_{Winf} \rightarrow AB = (1 - C_{extra}) \times AB_{Winf} \tag{7}$$

4 Simulation Results

This section shows simulation results of our proposed congestion control mechanism. The results are obtained using the ns-2 simulator [15]. The underlying *rt-Winf* mechanism is configured with enabled RTS/CTS/ACK handshake packets. The proposed mechanism is evaluated against the base TCP-AP protocol and against XCP-b and XCP-Winf. Several scenarios were used, varying the number of nodes and the traffic load. XCP-Winf and rt-Winf ns-2 implementations will, as soon they are validated by the ns2 community, be publicly available. In the simulations we used a mesh topology scenario with a grid of 16 mesh nodes and a variable number of mobile nodes. The number of mobile nodes changed from 3 to 7. It was also defined some ad hoc scenarios. These scenarios were composed of 8, 16, 32, 64, 128 and 256 nodes, and for each scenario 4, 8, 16, 32, 64 and 128 simultaneous flows. The routing protocol used was the Destination-Sequence Distance-Vector (DSDV) [18]. All simulations last 300 seconds. The simulations were repeated 30 times with different ns-2 seed values, and both the mean and 95% confidence intervals are presented in the results. The configured default transmission range was 250 meters, the default interference range is 500 meters, and the channel data rate is 11 Mbps. The performance metrics used are: throughput, delay and number of received packets.

For the data transmissions, it is used a File Transfer Protocol (FTP) application with packets of 1500 bytes or a Constant Bit Rate (CBR) application simulating a VoIP application. The mobility is emulated through the ns-2 setdest tool to provide a random node movement pattern. We configure setdest with a minimum speed of 10 m/s, a maximum speed of 30 m/s and a topology boundary of 1000x1000 meters. All results were obtained from ns-2 trace files, with the help of trace2stats [19] scripts adapted to our own needs.

Figure 1, Figure 2 and Figure 3 show the previous metrics for the mesh scenarios. Figure 1 shows how throughput is improved in *boosted-TCP-AP*. The *boosted-TCP-AP* throughput values are $\sim$ 10% to $\sim$ 30% better than the ones with the standard TCP-AP. In terms of received packets, as observed in Figure 3, it is possible to see that using rt-Winf with TCP-AP it is possible to receive more packets, this is due to a more effective link and available bandwidth estimation, and also the fact that *boosted-TCP-AP* has a collision probability factor, thus reducing the number of lost packets. The network, with this improvements, can transmit with a higher rate and less losses. As more packets are transmitted, more throughput is obtained and the medium is better used. This allows to have a more stable and fair behavior. It is, however, important to say that TCP-AP has a very conservative behavior, as it allows a good throughput with less received packets. This behavior, while not totally eliminated, is clearly improved with *boosted-TCP-AP*. The delay values, Figure 2 are also reduced reinforcing the fact that this new proposal is much more efficient and fair than the standard protocol. *boosted-TCP-AP* outperforms XCP-b, especially in terms of throughput due to the previously referred problems of XCP-b in high mobility scenarios. The better results are obtained by XCP-Winf, but it is clear that the use of rt-Winf is making *boosted-TCP-AP* to react more efficiently to the network dynamics.

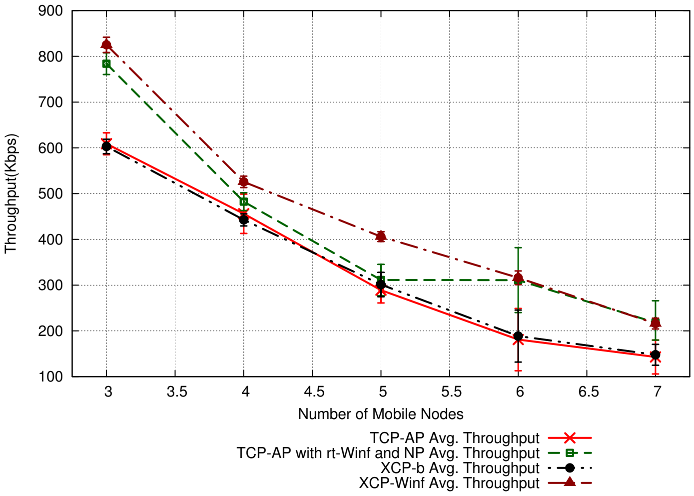

Figure 1: 16 Mesh Nodes - Variable Number of Mobile Nodes, Throughput.

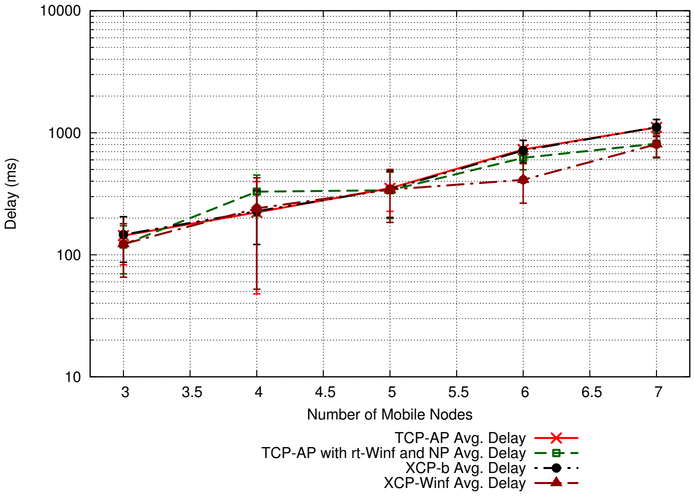

Figure 2: 16 Mesh Nodes - Variable Number of Mobile Nodes, Delay.

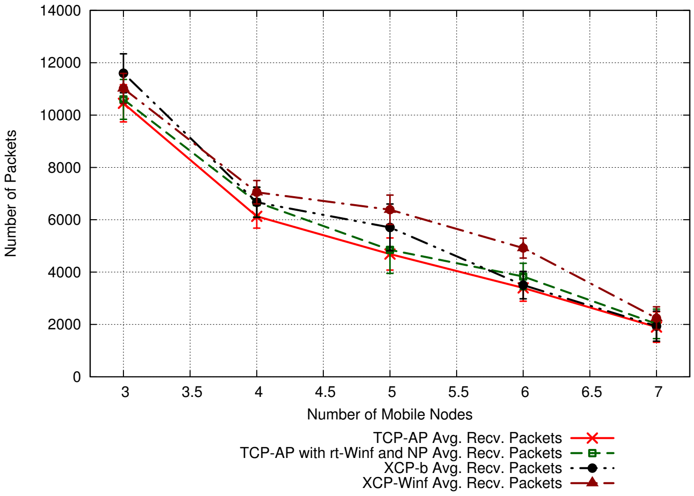

Figure 3: 16 Mesh Nodes - Variable Number of Mobile Nodes, Received Packets.

Figure 4, Figure 5 and Figure 6 show the results for the ad hoc networks, using CBR flows, as defined before. Form the observation of the results it is possible to conclude that TCP-AP with rt-Winf integrated and node path contention clearly improves TCP-AP performance behaviour. It is possible to conclude that, with more nodes and flows in the network, *boosted-TCP-AP* is more efficient than the standard TCP-AP proposal and then XCP-b. XCP-Winf, as this is a pure rate based explicit congestion control notification mechanisms using MAC layer information, is operating more efficiently than *boosted-TCP-AP*, specially concerning the number of received packets. This is a consequence of the hybrid mechanism of *boosted-TCP-AP*, using for flow and congestion control a rate based AIMD TCP process, not using the entire information of the MAC layer and as a consequence it operates in a more conservative way. Another difference between *boosted-TCP-AP* and XCP-Winf is that XCP-Winf uses a fairness module that allows it to be more accurate and effective. Once more, the results show that XCP-b is better suited when the number of mobile nodes is small. *boosted-TCP-AP*, as opposed to TCP-AP, is using all the network information, with the use of the node path contention count, making it behave more efficiently and allowing it to increase the flow rate, and consequently increase the number of received packets and reducing the overall delay. We can conclude that the available bandwidth and capacity evaluation of rt-Winf, estimated at the MAC layer, the collision probability and the node contention count factors are relevant and surely make *boosted-TCP-AP* behave more consistently and with better channel utilization, which also leads to less channel losses. Comparing both ad hoc and mesh results it is evident that *boosted-TCP-AP* results are better on the ad hoc environments, this is due to the fact that TCP-AP was developed having in mind ad hoc networks and, also, due to the fact that the underlying hybrid scheme of *boosted-TCP-AP* is better suited for ad hoc networks with high density and mobility.

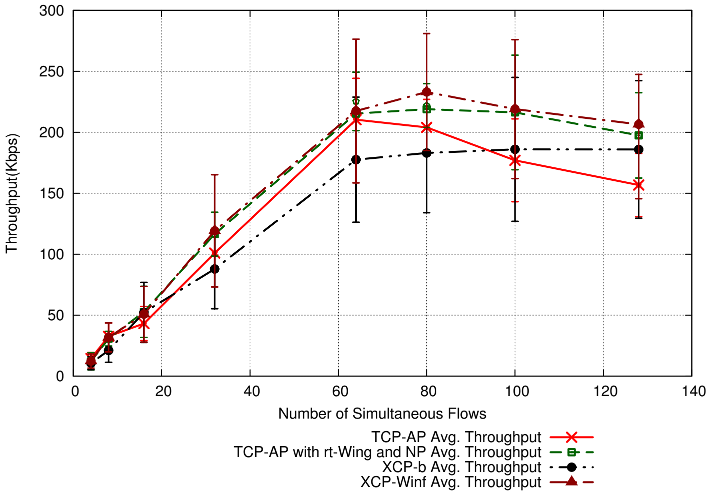

Figure 4: Ad-Hoc Scenario, Throughput.

As TCP is the most used and deployed congestion control protocol on the Internet, it is important, as described on [20], to analyze how *boosted-TCP-AP* flows interact and compete with TCP. For analysing how friendly *boosted-TCP-AP* is, we use the average data rate over time for each flow, thus, allowing to observe how bandwidth is being manage between TCP and the *boosted-TCP-AP* proposal. This is called the utility of a congestion control mechanism against TCP. It was then defined two new scenarios, using *boosted-TCP-AP* and TCP. The scenarios consist of a 1000mx1000m area, divided on three distinct parts. An area of 250mx250m where

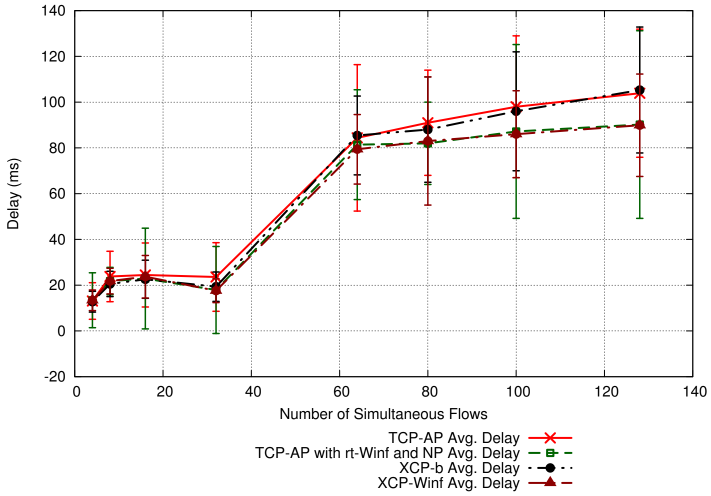

Figure 5: Ad-Hoc Scenario, Delay.

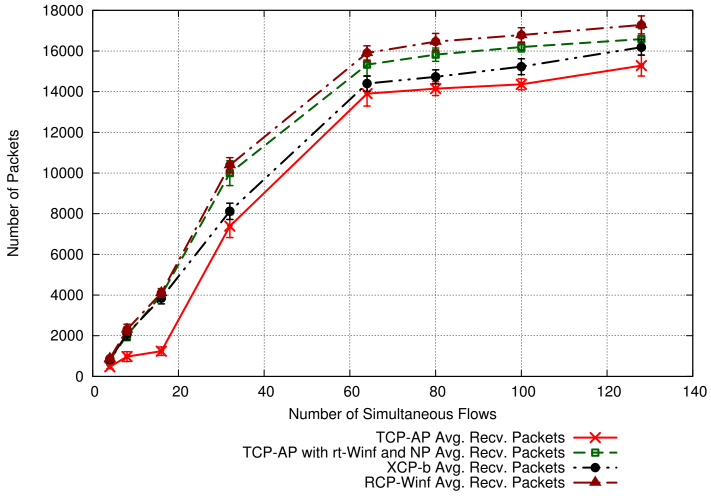

Figure 6: Ad-Hoc Scenario, Received Packets.

we have two mobile node sources one with TCP, and the other with *boosted-TCP-AP*; a middle area of 500mx500m with two mobile nodes with the *boosted-TCP-AP* mechanism as the main congestion control protocol, the average data rate is measure on this two nodes, as they will have TCP and *boosted-TCP-AP* like flows competing; finally another area of 250mx250m for the mobile nodes sinks. In one scenario we have each source generating eight FTP flows, with packets of 1500 bytes. In th other scenario we have each source generating sixteen FTP flows. The simulations last 120 seconds. The obtained results are shown on Figure 7 and Figure 8.

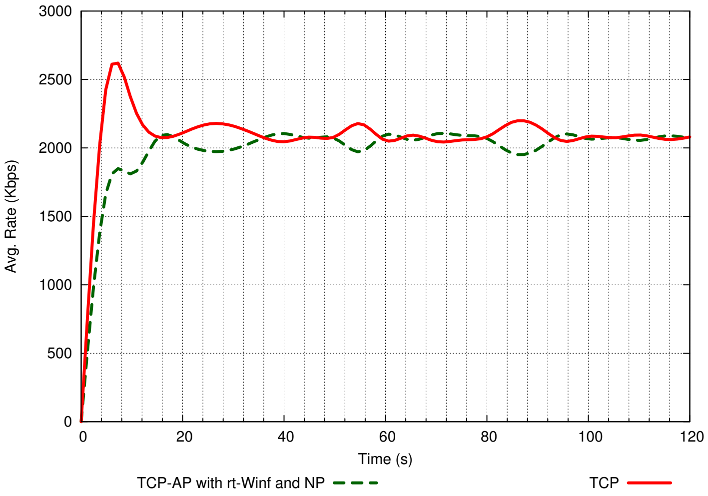

Figure 7: Utility Results, 2 x 8 Flows.

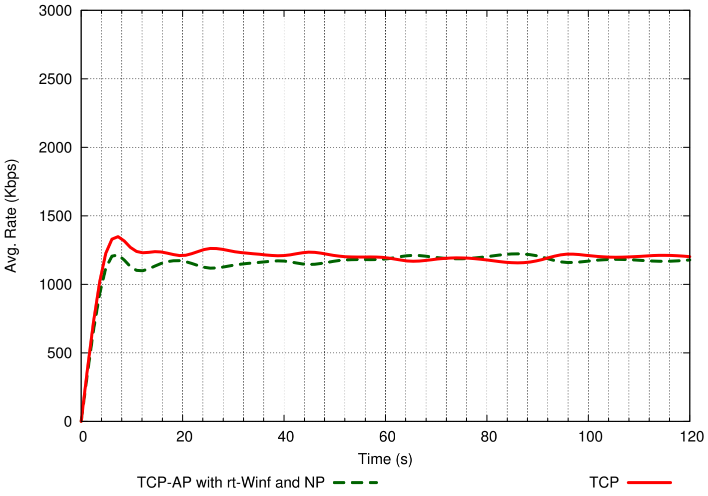

Figure 8: Utility Results, 2 x 16 Flows.

From the utility results it is possible to observe that on both situations TCP flow grows faster and gains more on the beginning. However, as *boosted-TCP-AP* is an hybrid approach, keeping unchanged the AIMD process of TCP, and is updated with an evaluation and measurement process, it quickly adjusts to TCP behaviour, thus, allowing a fair share of network resources.

It was also important to understand how the factor R is influencing *boosted-TCP-AP* behaviour. A central network chain scenario was defined. On this scenario it was used the proposed version of *boosted-TCP-AP* and another version without the factor R. The chain scenario consists of a network divided in three parts. In the central zone we have chain nodes, which depending on the simulation, vary on number. On the lateral sides of the network we have four sending nodes and four receiving nodes. The application used simulates a FTP transfer. The results are shown on Figure 9, Figure 10 and Figure 11. The presented results clearly state that for better accuracy and behaviour of *boosted-TCP-AP*, the available bandwidth and capacity estimation must consider the nodes along the path between the source nodes and the sink nodes, that is, the contending successors and predecessors on the route path. It is, then, proved that the factor R, which represents the proportion of bandwidth contention among other nodes on the path, is maximizing the throughput while guaranteeing fairness.

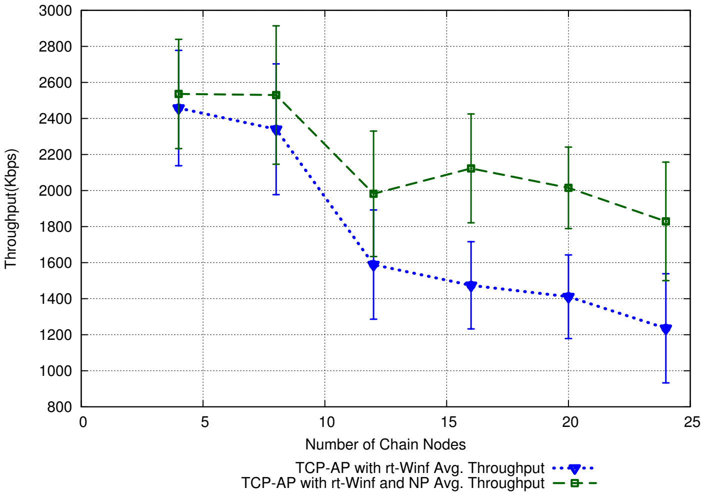

Figure 9: Chain Scenario, Throughput.

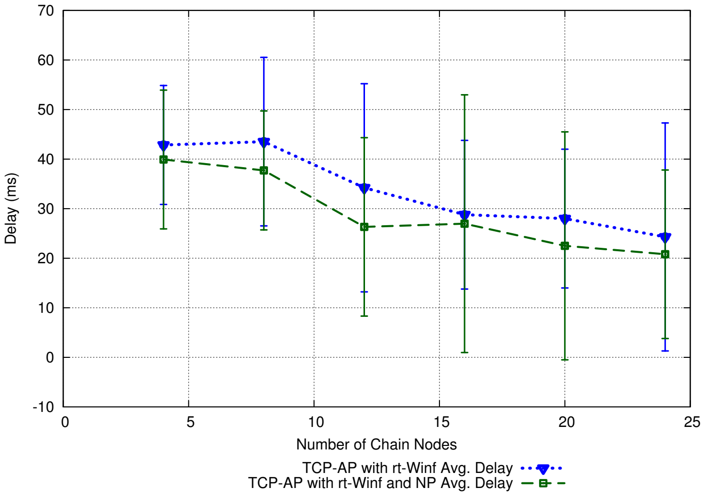

Figure 10: Chain Scenario, Delay.

5 Conclusions

This paper proposed a new approach to congestion control, based on TCP-AP and rt-Winf, for wireless environments. rt-Winf measures the wireless capacity and the available bandwidth of wireless links, and feeds this information to TCP-AP, through a cross layer communication

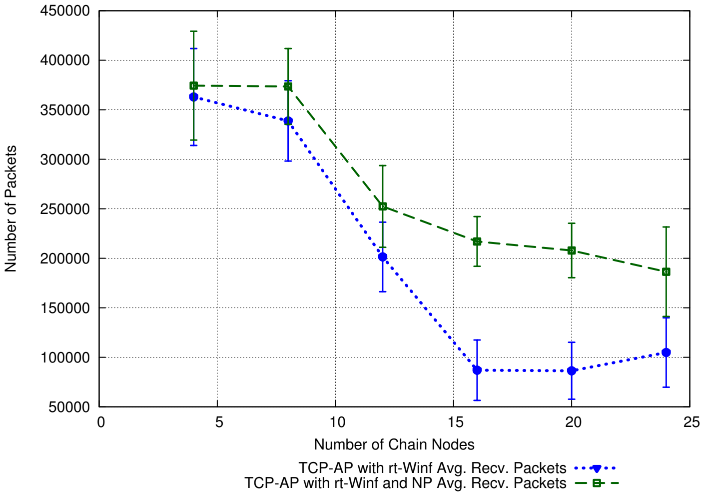

Figure 11: Chain Scenario, Received Packets.

process. Two different factors were also considered on the new approach, collision probability and node path contention count.

The performance evaluation study of the proposed congestion control mechanism shows that the integration of the rt-Winf algorithm, and the collision probability and node path count, improves significantly TCP-AP behaviour, making it more efficient and effective. TCP-AP used a four hop propagation delay for its functioning that in high mobility networks is not very accurate. The new congestion control mechanism uses information from the the MAC layer, where link capacity and available bandwidth calculations are performed without interfering in the network dynamics, and introduces the concept of entire network knowledge.

As future work, we plan to work on the wider evaluation of the congestion control approach, using, for example, new comparison baselines and protocols and different bit rates. An effort will also be made in creating a future test bed for understanding the proposed mechanism is affected by different conditions and parameters, in a real environment.

References

[1] J. Postel, “Transmission control protocol,” RFC 793, Defense Advanced Research Projects Agency, September 1981. [Online]. Available: http://www.rfc-editor.org/rfc/rfc793.txt

[2] I. F. Akyildiz, X. Wang, and W. Wang, “Wireless mesh networks: a survey,” *Computer Networks*, vol. 47, no. 4, pp. 445 – 487, 2005. [Online]. Available: http://dx.doi.org/10.1016/j.comnet.2004.12.001

[3] B. Res, L. Barreto, and S. Sargento, “rt-winf: Real time wireless inference mechanism,” *IEEE Globecom 2010 Workshop on Mobile Computing and Emerging Communication Networks (MCECN 2010)*, pp. 1130–1135, Dec 2010. [Online]. Available: http://dx.doi.org/10.1109/GLOCOMW.2010.5700111

[4] S. M. ElRakabawy, A. Klemm, and C. Lindemann, "TCP with pacing for multihop wireless networks," in *Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing*, ser. MobiHoc '05. ACM, 2005, pp. 288–299.

[5] L. Barreto and S. Sargento, "XCP-winf and RCP-winf: Improving explicit wireless congestion control," *Journal of Computer Networks and Communications*, p. 18, 2015. [Online]. Available: http://dx.doi.org/10.1155/2015/925207

[6] S. Rangwala, A. Jindal, K.-Y. Jang, K. Psounis, and R. Govindan, "Understanding congestion control in multi-hop wireless mesh networks," in *Proceedings of the 14th ACM international conference on Mobile computing and networking*, ser. MobiCom '08. ACM, 2008, pp. 291–302. [Online]. Available: http://dx.doi.org/10.1145/1409944.1409978

[7] K.-Y. Jang, K. Psounis, and R. Govindan, "Simple yet efficient, transparent airtime allocation for tcp in wireless mesh networks," in *Proceedings of the 6th International Conference*, ser. Co-NEXT '10. New York, NY, USA: ACM, 2010, pp. 28:1–28:12. [Online]. Available: http://dx.doi.org/10.1145/1921168.1921205

[8] M. Li, D. Agrawal, D. Ganesan, and A. Venkataramani, "Block-switched networks: A new paradigm for wireless transport," in *Proceedings of the 6th USENIX Symposium on Networked Systems Design and Implementation*, ser. NSDI'09. Berkeley, CA, USA: USENIX Association, 2009, pp. 423–436.

[9] A. Aziz, D. Starobinski, P. Thiran, and A. El Fawal, "Ez-flow: Removing turbulence in ieee 802.11 wireless mesh networks without message passing," in *Proceedings of the 5th International Conference on Emerging Networking Experiments and Technologies*, ser. CoNEXT '09. New York, NY, USA: ACM, 2009, pp. 73–84. [Online]. Available: http://dx.doi.org/10.1145/1658939.1658948

[10] K. Xu, M. Gerla, L. Qi, and Y. Shu, "Enhancing tcp fairness in ad hoc wireless networks using neighborhood RED," in *Proceedings of the 9th Annual International Conference on Mobile Computing and Networking*, ser. MobiCom '03. New York, NY, USA: ACM, 2003, pp. 16–28. [Online]. Available: http://dx.doi.org/10.1145/938985.938988

[11] F. Abrantes and M. Ricardo, "A simulation study of XCP-b performance in wireless multi-hop networks," in *Proceedings of the 3rd ACM workshop on QoS and security for wireless and mobile networks*, ser. Q2SWinet '07. ACM, 2007.

[12] L. Barreto and S. Sargento, "XCP-winf and RCP-winf: Congestion control techniques for wireless mesh networks," in *IEEE International Conference on Communications (ICC 2011)*, Kyoto, Japan, 2011. [Online]. Available: http://dx.doi.org/10.1109/icc.2011.5963464

[13] D. Katabi, M. Handley, and C. Rohrs, "Congestion control for high bandwidth-delay product networks," *SIGCOMM Comput. Commun. Rev.*, vol. 32, no. 4, pp. 89–102, Aug. 2002. [Online]. Available: http://dx.doi.org/10.1145/964725.633035

[14] N. Dukkipati and N. McKeown, "Why flow-completion time is the right metric for congestion control," *SIGCOMM Comput. Commun. Rev.*, vol. 36, no. 1, pp. 59–62, Jan. 2006. [Online]. Available: http://dx.doi.org/10.1145/1111322.1111336

[15] “The network simulator - ns-2,” 2001. [Online]. Available: http://www.isi.edu/nsnam/ns/

[16] M. Conti, G. Maselli, G. Turi, and S. Giordano, “Cross-layering in mobile ad hoc network design,” *Computer*, vol. 37, pp. 48–51, 2004. [Online]. Available: http://dx.doi.org/10.1109/MC.2004.1266295

[17] *IEEE Std 802.11 - IEEE Standard for Information technology Telecommunications and information exchange between systems Local and metropolitan area networks Specific requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Computer Society Standard, 2007. [Online]. Available: http://standards.ieee.org/getieee802/download/802.11-2007.pdf

[18] C. E. Perkins and P. Bhagwat, “Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers,” *SIGCOMM Comput. Commun. Rev.*, vol. 24, no. 4, pp. 234–244, Oct. 1994. [Online]. Available: http://dx.doi.org/10.1145/190809.190336

[19] M. Fiore, “trace2stats.” [Online]. Available: http://perso.citi.insa-lyon.fr/mfiore/research.html

[20] J. Feng and L. Xu, “TCP-friendly CBR-like rate control,” in *Network Protocols, 2008. ICNP 2008. IEEE International Conference on*, Oct 2008, pp. 177–186. [Online]. Available: http://dx.doi.org/10.1109/ICNP.2008.4697036

Copyright Disclaimer