Improvement for Rate-based Protocols in Multihop Wireless Networks

Le Minh DUONG, * Lynda ZITOUNE, ** Véronique VÈQUE
University of Engineering and Techonology, VNUH
* Dept. of Embedded Systems - ESIEE-Paris
** Laboratory of Signals and Systems - Supélec
Email: minhdl@vnu.edu.vn l.zitoune@esiee.fr veronique.veque@u-psud.fr

***Abstract*—Transport layer performance in IEEE 802.11 multihop wireless networks (MHWNs) has been greatly challenged by wireless medium characteristics and multihop nature which induce several types of packet loss including collision, random channel errors and route failures. In this paper, we propose a novel rate control scheme, called Bi-Metric Rate Control (BMRC), which regulates efficiently the source rate in MHWNs. BMRC's design is based on two MAC metrics: the Medium Access Delay used to detect the network contention level, and the Average Transmission Time used to estimate the effective packet sending rate by which the network will not be overloaded. The simulation results show that the adapted mechanism introduces significant performance improvement in terms of fairness, packet loss rate and delay in MHWNs.**

I. Introduction

The TCP performance degradation problem in Multihop Wireless Networks (MHWN) has been widely investigated in recent years [1] [2]. Degradation comes mainly from the shared wireless medium characteristics such as interference, error prone channels and the multihop nature of MHWNs. One of the major approaches to address this issue is the cross-layer between MAC and Transport layers, in which the MAC layer information is collected and provided upward to the transport layer. The transport protocols will have more knowledge on what happens at the lower network layers and thus can improve the performance [1] [3] [4] [5].

Our work interests in cross-layer improvement for rate-based congestion control, i.e. TCP-Friendly Rate Control (TFRC) [6], which is used for VoIP or streaming applications. Although TFRC works well for streaming applications in wired line networks, [7] and [8] show that TFRC is very conservative in MANETs due to inaccuracy of loss prediction and unreliable delay measurement. Thus, there is a need for a new rate control mechanism based on MAC information which could operate efficiently in MHWNs.

The aim of this work is to propose a new rate regulation method which adapts the source bit rate based on the MAC layer contention level. Indeed, with these improvements and the fact that the congestion couples closely with the contention as demonstrated in [8] [9], it is feasible to improve the performance of transport protocols by considering only the contention state of the network. The contention growth event should be detected as early and accurately as possible, and there should be a mechanism which can react efficiently to this event in order to reduce the effect of high contention level in the network.

In our previous work [10], we proposed a new MAC metric, named Medium Access Delay (MAD), which is very effective in reflecting the network contention level. Then, in the work [11], we proposed a new rate control scheme based on the MAD metric, called MAD-TP, which can early detect the contention growth event in MHWNs and control efficiently the traffic rate sent throughout the network. Our simulation results showed that MAD-TP outperforms TFRC in terms of critical real-time criteria which are the end-to-end delay and the packet loss ratio. Moreover, MAD-TP also exhibits a better result in almost all scenarios compared to that of LATP, a recent proposal for real-time streaming applications in MHWNs [12]. However, MAD-TP has a drawback that MAD has no explicit correlation with the transmission rate. Thus, the transmission rate formula, which is relies on the threshold MAD_{TH}, is not fully reliable.

In this paper, we propose a new rate-based transport protocol which addresses the shortcomings of the former MAD-TP, while exhibits a better performance. Our proposal called Bi-Metric Rate Control (BMRC) is based on two metrics introduced in [10]: the Medium Access Delay (MAD) used to early determine whether the network enters into high contention/collision level, and the Average Transmission Time (ATT) used to estimate an effective sending rate to prevent the flow from severe performance degradation.

The paper is organized as follows. Section II provides a brief description of the MAC metrics and our previous proposal MAD-TP. The design of BMRC is described in detail in Section III. Section IV exhibits the simulation scenarios and results. Finally, we conclude the paper in Section V.

II. MAD-TP and MAC Metrics for Network State Estimation

In our previous work [10], we proposed two effective metrics, named Medium Access Delay (MAD) and Average Transmission Time (ATT). The Medium Access Delay, MAD, is defined as the average total contention delay for a packet at MAC layer before it is successfully transmitted or dropped after several failed retransmissions in an interval. The definition of the Average Transmission Time, ATT, is derived from that of the MAC Service Time T_{srv} which is the time interval from the time instant a frame starts to contend for transmission to the time instant the transmitter receives correctly the MACK of that frame or drops it after several failed retransmissions [13]. ATT is the average MAC service time of a successfully transmitted packet in an interval. By these definitions, it is clear that MAD is a part of ATT.

The results of our previous work [10] showed that MAD and ATT appear as the most effective metrics which provide the accurate information about network contention/collision level. MAD is very sensitive to the network contention level so in our first rate-control proposal, MAD-TP [11], we used MAD as an early indication of the contention increase event. The MAD-TP sender adapts its sending rate according to the average value of the average cumulative MAD measurement along the connection path provided in the feedback packet. Depending on the comparison between received MAD and a threshold MAD_{TH}, the sender decides whether the network is in saturated or non-saturated state and controls its sending rate appropriately in order to keep the network operation under a stable state with a reasonable contention level. The control rules are explained in detail in [11]. Our simulation results in [11] showed that MAD-TP outperforms TFRC and LATP in terms of End-to-End delay and Packet Loss Ratio which are the two critical criteria for streaming applications, but at the price of a slight degradation in connection throughput. In this paper, to overcome the drawback of MAD-TP's transmission rate formula and to improve the contention detection capability, we propose to use the MAD gradient to determine if the network enters into severe contention level. In addition, we use another metric, ATT, which is relative to the effective bandwidth in order to estimate the maximum sending rate of the sender.

The next section will detail BMRC, a Bi-Metric Rate Control mechanism which is based on MAD and ATT to adapt appropriately the sending rate in MHWNs.

III. BMRC: THE BI-METRIC RATE CONTROL

The BMRC scheme is aimed at providing an efficient rate control mechanism at transport layer which can reduce the contention effect of MHWNs. The design of BMRC is derived from MAD-TP [11], in which we have added the use of MAD gradient and ATT.

A. Intermediate nodes

The role of intermediate nodes is to provide estimation of contention level experienced by each node along the connection path. Each node maintains the measurement of MAD and ATT in every interval. In our implementation, we chose the interval duration to 0.1 seconds as the trade-off between the smoothness and the effectiveness as in [11].

For every packet passing the node, it adds its MAD and ATT values respectively to the existing values stored in option fields in the IP header, called Cumulative MAD (CMAD) and Cumulative ATT (CATT). The maximum ATT along the path is also stored in another option field of the IP header, called MATT. Due to [10], each of three option fields needs only one byte to store the time value (in ms). With this protocol, when the packet reaches the destination, the CMAD, CATT and MATT fields will contain respectively the cumulative contention delay, transmission delay and maximum transmission delay along the connection path.

B. BMRC receiver

The function of the BMRC receiver is to calculate some important parameters and to feed them back to the sender.

Every time receiving a packet, it takes the $CMAD$, $CATT$ and $MATT$ values from CMAD, CATT and MATT fields, and the number of hops, noted N_h, from TTL field in the IP header or from the routing table of source routing protocols and compute the $MAD_{sample} = CMAD/N_h$. The BMRC receiver then derives the mean contention delay per hop by using the Exponentially Weighted Moving Average (EWMA) function with $\beta = 0.5$ as follows:

$$MAD = \beta MAD + (1 - \beta) MAD_{sample} \tag{1}$$

This mean value is calculated as in equation 1 for every received packets.

The BMRC receiver also uses $CATT$ and $MATT$ to estimate the upper bound of bandwidth-delay product of the connection path as suggested in [14]. The authors claimed that, in a IEEE 802.11-based MANET where the interference range is set to double of the transmission range, the upper bound of the bandwidth-delay product (BDP_{UB}) of a chain of nodes can be estimated by the per-hop packet transmission delays along the forward and return paths. From the definitions of the ATT metric and the per-hop packet transmission delay (d_i) [14], if d_i is averaged in an interval, then we have $d_i \simeq ATT$.

In [14], BDP_{UB} is computed for each pair of TCP data and ACK packets. However, in the case of rate-based transport protocol, the feedback packet is not generated for each arrived data packet but for every interval of time, i.e. a round trip time, or for every new detected loss event (for TFRC). Therefore, we can reasonably deduce the equation of BDP_{UB} in [14] that

$$\begin{aligned} BDP_{UB} &\simeq S \times \frac{\sum_{i=0}^{n} ATT_i + \sum_{i=0}^{m} ATT'_i}{4 \times ATT_{max}} \\ &\simeq S \times \frac{2 \times \sum_{i=0}^{n} ATT_i}{4 \times ATT_{max}} \\ &\simeq S \times \frac{CATT}{2 \times MATT} \end{aligned} \tag{2}$$

where S is the packet size, n and m are the number of hops in the forward and reverse paths, and ATT_{max} is the maximum ATT value on the paths.

The BMRC receiver uses also the EWMA function to derive the mean value of BDP for each received packet as follows:

$$BDP = \mu BDP + (1 - \mu) BDP_{UB} \tag{3}$$

Since BDP value is used to estimate the packet sending rate, we set $\mu = 0.9$ to guarantee the smoothness.

The feedback mechanism of BMRC is the same as in MAD-TP [11], except that the receiver sends also the calculated BDP.

C. BMRC Sender

Upon receiving MAD and BDP values from the feedback packet, the sender computes the MAD gradient and the maximum sending rate R_{UB}.

Denote A_i and A_{i+1} respectively the arrival time of the feedback packets i^{th} and $(i+1)^{th}$, MAD_i and MAD_{i+1} the corresponding attached MAD values, then the MAD gradient α is:

$$\alpha = \frac{MAD_{i+1} - MAD_i}{A_{i+1} - A_i} \tag{4}$$

We built a simulation evaluation scenario with a chain topology to determine the distribution of α values in both non-saturated and saturated states of the network depending on the offered load. Due to the page limitation, we explain only some noticeable results of the evaluation. The results showed that when the network is not overloaded, i.e. non-saturated state, the packet loss rate is low, the end-to-end delay is small. Almost all values of α fall into the range of [-5, 5]. This can be interpreted that, in the optimal network load point, the MAD gradient should not exceed the value of 5. When the network is overloaded, the values of α then distribute over a larger range.

From those results, we then may define two thresholds $0 < TH_1 < TH_2$ which are used as the indicators of network contention level. If $\alpha < TH_1$, it means that the MAD decreases (in case $\alpha < 0$) or it increases relatively small ($0 < \alpha < TH_1$), the traffic source thus can properly increase its sending rate. We set $TH_1 = 5$. If $\alpha > TH_2$, there is a risk that the network enters into severe contention state. The traffic source should not increase the sending rate in this case. We set $TH_2 = 7$ in order to react quickly to the sudden increase of the network contention level. Otherwise, i.e. $TH_1 < \alpha < TH_2$, the network may operate in a reasonable point and the traffic source keeps its current sending rate unchanged. Note that the two values of TH_1 and TH_2 (5 and 7) were chosen as the most loose case for a simple chain topology since this topology provides a clear view on the effect of α. However, we will prove later that, even with these unoptimized values, our proposed mechanism still provides a better result in other topologies in comparison to the ones of [6] and [12].

The upper bound for the sending rate R_{UB} can be computed from BDP and current Round-trip Time RTT as follows:

$$R_{UB} = \frac{BDP}{RTT} \tag{5}$$

R_{UB} is thus the maximum sending rate by which the network is not overloaded. Afterwards, in order to avoid frequent changes, the sending rate is updated by the following rule:

```
if (R_UB > R && α < TH_1)
      increase rate
elseif (R_UB < R && α > TH_2)
      decrease rate
```

where R is the current sending rate.

The BMRC sender decreases the sending rate using the same rule in LATP [12], by which the sending rate is reduced by 1/8 its current sending rate after each RTT but never smaller than one packet per RTT. To increase the rate, in case of $\alpha < TH_1$, BMRC sender applies the following equation

$$R = min(R_{UB}, R + N * S/RTT) \tag{6}$$

Equation 6 ensures that the new rate does not exceed the upper bound rate and increases of at most one packet per RTT. Note that the sending rate is always greater than one packet per RTT with these increase and decrease rules.

IV. Simulation and Results

The performance evaluation for our rate control proposal BMRC is carried out in comparison with MAD-TP, TFRC and LATP. We use NS-2 simulator version 2.34 [15] to conduct the evaluation with the general configuration parameters as in Table I. In all topologies, the nodes in the MHWNs are static to reduce the effect of mobility and the channel is set to be perfect to eliminate the effect of channel error losses. In the simulation, BMRC, MAD-TP, TFRC and LATP operate as they always have packets to send, thus their operation does not depend on the application rate. The performance metrics are: Throughput, End-to-End (E2E) Delay, Packet Loss Ratio (PLR) and Fairness. They are averaged from 16 simulation runs of $400s$ in each scenario.

TABLE I: General configuration for simulation

Parameters	Value
Propagation Model	TwoRayGround
MAC protocol	802.11 DCF
Channel Capacity	6Mbps
Interface queue size	50
Carrier Sensing Range	$\simeq$ 500m
Transmission Range	$\simeq$ 250m
Data packet size	1000 bytes
Routing protocol	AODV

A. Scenarios

We used the same scenario setup as in our previous work [11], briefly described as follows.

We consider three types of topology, chain, grid and random, because of the variety of interference schemes they represent. In chain topology, a pair of nodes is 200m apart. The first scenario considers one flow connection over a chain topology of varying number of hops. The second scenario is a chain topology with 8 hops and 4 parallel connections. The third scenario is a grid topology of 8x8 nodes where 4 connection patterns are set up such that they provide different contention levels in the network. The fourth scenario uses a random topology with 60 nodes placed randomly in 1500mx1500m area. The number of connections running simultaneously in the network is 5, 10, 15 and 20.

The simulation results are explained in the following sections.

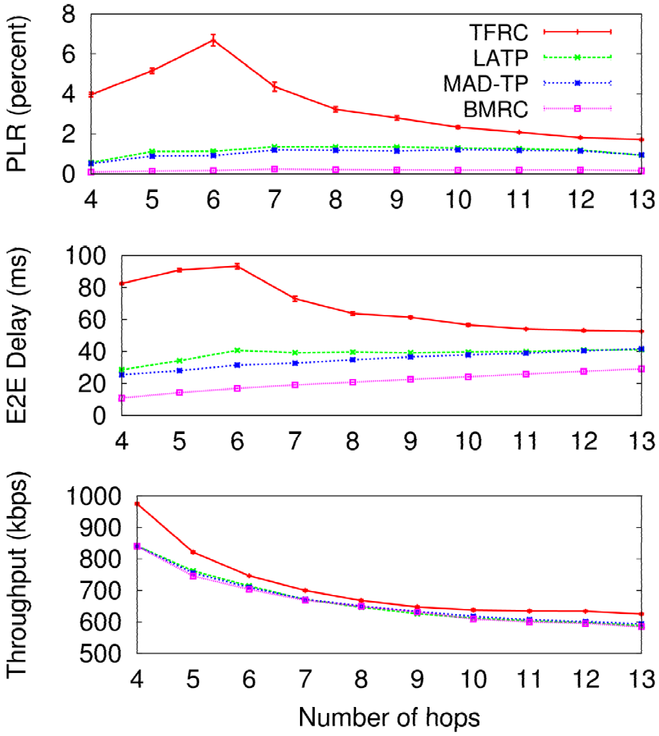

Fig. 1: Chain topology with 1 connection

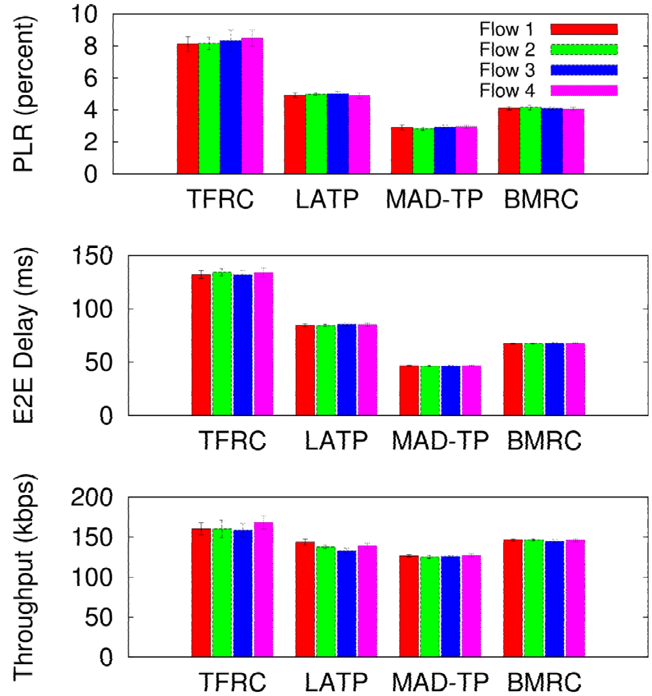

Fig. 2: Chain topology with 8 hops and 4 connections

B. Results and discussion

Chain topology

In Figure 1, BMRC exhibits a better performance in terms of PLR and E2E delay in comparison with the other protocols. The PLR of BMRC ranges from 0.1% (for 4 hop chain) to 0.25% (for 7 hop chain), while those of MAD-TP, LATP and TFRC are respectively [0.5%, 1%], [0.6%, 1.4%] (all for 4 and 7 hop chain) and [1.7%, 6.7%] (for 13 and 6 hop chain). These values mean that the average PLR value of BMRC is approximately equal to 1/4, 1/5 and 1/20 that of MAD-TP, LATP and TFRC respectively.

BMRC also achieves much lower E2E delay than other considered protocols and the increase of E2E delay reflects adequately the increase of the number of hops. Although MAD-TP has the same behavior as BMRC, the E2E delay introduced by MAD-TP is larger than that of BMRC. There is always a difference of about 10 ms between the E2E delay of MAD-TP and BMRC for all number of hops. Another noticeable point is that, although BMRC exhibits smaller PLR and E2E delay, it keeps almost the same throughput as MAD-TP and LATP, and a little smaller than that of TFRC. This is the price BMRC has to pay to achieve much better PLR and E2E delay. However, for applications which have strict packet drop rate and latency, we believe that this trade-off is acceptable.

TFRC's rate control wrongly estimates the network capacity and tends to overload the network which has limited resources. This problem is caused by the sending rate equation used in TFRC which depends on inaccurate packet loss rate measurement in MHWNs [7], where losses are mostly due to channel contention. Thus, TFRC increases the rate inappropriately when the network contention is rather high and does not decrease the rate efficiently enough when the network contention becomes severe. As a consequence, the packets transmitted along the path will suffer from high loss rate and delay caused by collision among contending nodes, multiple retransmission attempts at MAC layer as well as high level of channel busyness.

LATP detects the network condition better than TFRC by using the Permissible Throughput metric [12]. LATP's rate control based on this metric is also more efficient than that of TFRC. Thus, LATP achieves better performance than TFRC.

However, BMRC outperforms LATP since BMRC uses the MAD metric which detects contention state better than the Permissible Throughput metric. BMRC uses also a more accurate bandwidth estimation and a more efficient rate control scheme than those of MAD-TP, LATP and TFRC. The bandwidth estimation reflects accurately the current capability of the network, thus prevents the BMRC sender from overloading the network. The proposed rate control scheme also maintains a relatively smooth sending rate which in turn keeps the network steady. Thus, BMRC always tries to make the network operate in a low contention level status which in turn reduces the transmission attempts to successfully transmit a packet as well as the delay a packet experiences.

Figure 2 shows the results for scenario with 4 connections. In this scenario, BMRC outperforms TFRC in terms of PLR and E2E delay with a price of an insignificant degradation

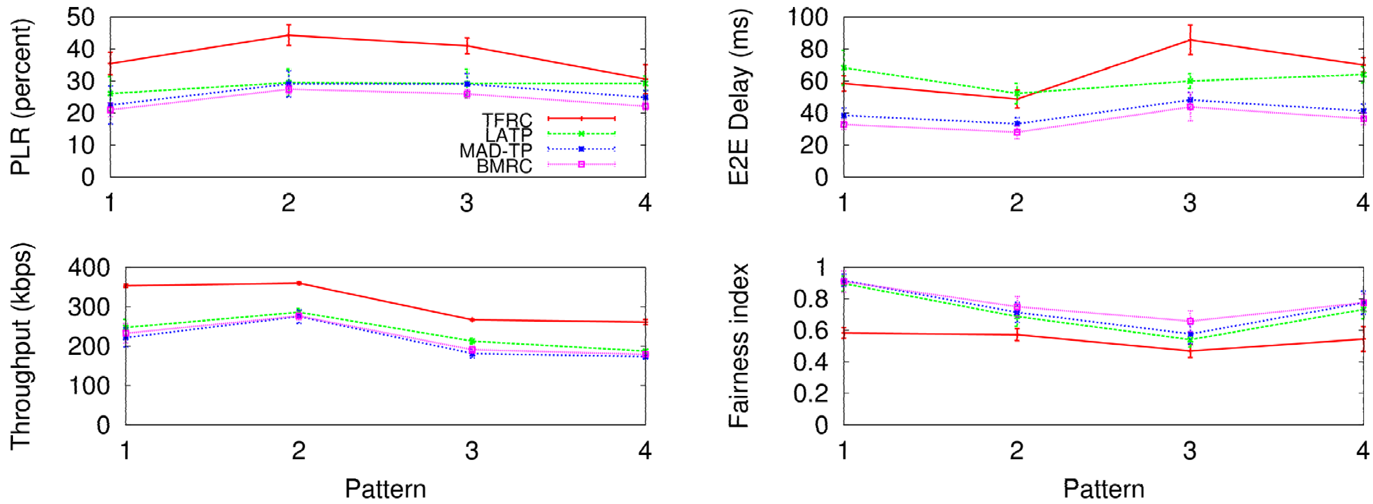

Fig. 3: Simulation results in grid topology

TABLE II: Simulation results for random topology

Flow #:	5				10				15				20			
	PLR	**Delay**	**Thpt**	**Fairness**	**PLR**	**Delay**	**Thpt**	**Fairness**	**PLR**	**Delay**	**Thpt**	**Fairness**	**PLR**	**Delay**	**Thpt**	**Fairness**
TFRC	20.71	166.47	134.34	0.51	33.49	413.06	126.54	0.23	38.35	506.78	90.26	0.24	45.30	772.88	138.99	0.18
LATP	11.06	64.03	108.66	0.79	22.87	162.79	95.22	0.37	22.83	178.31	62.75	0.42	22.22	181.37	85.51	0.25
MAD-TP	10.24	55.68	99.38	0.78	19.01	94.40	81.97	0.44	21.20	140.93	56.15	0.44	22.55	174.72	87.42	0.25
BMRC	9.7	52.6	92.5	0.78	17.1	88.3	82.8	0.48	20.1	103.8	58.4	0.53	20.4	121.8	90.7	0.28

of throughput. Moreover, the performance of BMRC is better than that of LATP in all three factors. Indeed, the PLR and E2E delay of BMRC are smaller than those of LATP by an amount of 0.8% and 17 ms, while the higher amount of throughput is 8 kbps. Note that this scenario has four connections which send more packets into the network than the previous scenario. Since the network capacity is unchanged, the network contention level becomes higher than that in the previous scenario due to the increase of packet number pumped into the network. These results again prove that the rate control mechanism of our proposed scheme is more effective. The BMRC's performance in terms of PLR and E2E delay is however worse than that of MAD-TP but with a better throughput. The reason is that MAD-TP uses MAD_{TH} to restrict the behavior of the sender and the rate will be decreased as soon as the received MAD surpasses this threshold. Therefore, the network with MAD-TP flows works at a point close but lower than the optimal point. In contrast, BMRC with its accurate and effective rate control makes the network working around the optimal point. This fact makes MAD-TP experiencing smaller PLR, E2E delay and Throughput than BMRC.

Grid Topology

In this scenario, BMRC introduces the best performance in comparison with other protocols. The E2E Delay and PLR measurements in Fig. 3 show that BMRC outperforms TFRC and LATP for all the connection patterns while maintaining a reasonable throughput. The average throughput of BMRC and LATP are slightly different. BMRC provides even better performance than that of MAD-TP.

Moreover, our simulation trace analysis showed that TFRC suffers from severe unfairness problem. Some flows achieve a very high throughput while that of other flows is very low, with a scale factor of 362. Although LATP exhibits a better result than TFRC, it does not totally eliminate the unfairness problem, i.e. the averaged flow throughput varies from 415 to 16 kbps, with a scale factor of 26 whereas MAD-TP has a throughput between 348 and 17 kbps and a scale factor of 20. BMRC outperforms both TFRC and LATP in terms of fairness since the average minimum flow throughput is higher and the considered scale is much smaller than those of TFRC and LATP (31.3 kbps and a scale factor of 10). Fig. 3 also shows that BMRC improves the Jain's fairness index by about 0.18 $\sim$ 0.32 at a price of 23% $\sim$ 32% drop in aggregate throughput compared to TFRC.

This prominence in fairness comes from the early detection of high network contention level and a reasonable rate control of BMRC. The BMRC flows can early realize that the network is becoming overloaded and thus will reduce appropriately the sending rate to release more bandwidth for other flows. The increase of BMRC flows' rate is also not aggressive, hence the channel is better shared among flows.

Random Topology

Table II displays the simulation results for the grid topology. As same, even in such a complex simulation scenario, BMRC still outperforms TFRC in terms of fairness, PLR and E2E delay. BMRC also provides a better performance than LATP in terms of fairness, PLR and E2E delay with the same throughput.

Finally, for the most realistic scenarios, we can conclude that BMRC is more efficient than the others.

V. Conclusion

In this paper, the new BMRC scheme has been proposed as an effective rate control for rate-based transport protocols in MHWNs. In BMRC, two metrics MAD and ATT are combined to provide a faster and more accurate network contention/collision detection within a refined rate regulation. BMRC is based on the gradient of MAD in order to detect the growth of network contention level. Two corresponding thresholds for MAD gradient are defined in the rate regulation mechanism. In addition to the contention detection task, BMRC also uses ATT metric to accurately estimate the effective bandwidth for the connection flow, and thus derives the upper bound of the sending rate. This upper bound is the maximum rate that the BMRC sender can use to pump packets into the network without overloading it. Using these techniques, BMRC provides an accurate and efficient rate control scheme over Multi-hop Wireless Networks. The simulation results show that BMRC provides better fairness level between flows in MHWNs than that of LATP and TFRC. BMRC also outperforms TFRC and LATP in terms of End-to-End delay and Packet Loss Ratio which are the two critical criteria for real-time streaming applications.

However, BMRC still has some shortcomings which will be taken into account in our future work. The first one is the choice of the exact values for both thresholds, TH_1 and TH_2. Although the values found out by simulation work well in all the experiments, they need to be proved, i.e. using an analytical model. The second one is the assumption in the estimation of BDP that the forward path is the same as the return path. This assumption is not always correct. Thus, this estimation should also be improved.

References

[1] A. Hanbali and E. Altman, "A Survey of TCP over Ad Hoc Networks," *IEEE Communications Surveys and Tutorials*, vol. 7, pp. 22–36, 2005.

[2] Z. Fu, H. Luo, P. Zerfos, S. Lu, L. Zhang, and M. Gerla, "The impact of multihop wireless channel on tcp performance," *IEEE Transactions on Mobile Computing*, vol. 4, pp. 209–221, March 2005.

[3] H. Zhai, X. Chen, and Y. Fang, "Rate-based transport control for mobile ad hoc networks," in *Proceedings of IEEE WCNC'05*, pp. 2264–2269, 2005.

[4] E. Hamadani and V. Rakocevic, "A Cross Layer Solution to Address TCP Intra-flow Performance Degradation in Multihop Ad Hoc Networks," *Journal of Internet Engineering*, vol. 2, pp. 146–156, 2008.

[5] X. Zhang, W. Zhu, and N. Li, "TCP Congestion Window Adaptation Through Contention Detection in Ad Hoc Networks ," *IEEE Transactions on Vehicular Technology*, vol. 59, pp. 4578–4588, 2010.

[6] S. Floyd, M. Handley, J. Padhye, and J. Widmer, "TCP Friendly Rate Control (TFRC): Protocol Specification," 2008. RFC 5348.

[7] K. Chen and K. Nahrstedt, "Limitations of equation-based congestion control in mobile ad hoc networks," in *Proceedings of the 24th International Conference on Distributed Computing Systems Workshops - W7: EC (ICDCSW'04) - Volume 7*, ICDCSW '04, (Washington, DC, USA), pp. 756–761, IEEE Computer Society, 2004.

[8] K. Nahm, A. Helmy, and J. C. Kuo, "On interaction between mac and transport layers for multimedia streaming in 802.11 ad hoc networks," in *in Proc. SPIE ITCOM 2004*, 2004.

[9] H. Zhai, X. Chen, and Y. Fang, "Improving transport layer performance in multihop ad hoc networks by exploiting MAC layer information," *IEEE Transactions on Wireless Communications*, vol. 6, no. 5, pp. 1692–1701, 2007.

[10] L. M. Duong, L. Zitounel, and V. Veque, "A Medium Access Delay MAC aware Metric for Multihop Wireless Networks," in *IWCMC '12*, Aug 2012.

[11] L. M. Duong, L. Zitounel, and V. Veque, "MAC-aware Rate Control for Transport Protocol in Multihop Wireless Networks," in *PIMRC '12*, Sept 2012.

[12] P. Navaratnam, H. Cruickshank, and R. Tafazolli, "A link adaptive transport protocol for multimedia streaming applications in multi hop wireless networks," in *MobiMedia '07*, pp. 1–6, ICST, 2007.

[13] H. Zhai, X. Chen, S. Member, Y. Fang, and S. Member, "How well can the ieee 802.11 wireless lan support quality of service?," *IEEE Transaction on Wireless Communications*, vol. 4, pp. 3084–3094, 2005.

[14] K. Chen, Y. Xue, S. Shah, and K. Nahrstedt, "Understanding bandwidth-delay product in mobile ad hoc networks," *Computer Communications*, vol. 27, pp. 923–934, 2003.

[15] "The Network Simulator - NS-2." http://isi.edu/nsnam/ns/.