Cross-layer Design for IEEE 802.11 Wireless Ad-hoc Network Utility Maximization with Active Queue Management

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Abstract

In this paper, we study the problem of jointly solving the contention and congestion distributed control problem in a bounded queue wireless ad-hoc network. The resulting flow rates satisfy fairness criteria according to a given Network Utility Maximization (NUM) function. In recent years a number of papers have presented solutions to this problem that are based on network utility maximization algorithms. However, this work typically necessitates either complex computations, heavy signaling/control overhead, and/or approximated sub-optimal results. In this paper, we combine a specific network utility maximization problem with a simple and efficient queue management mechanism that we believe is appropriate for wireless ad-hoc networks. We employ and adapt the IEEE 802.11 protocol to work with the utility maximization algorithm for contention optimization. Finally, we show via NS-3 simulations that the proposed Cross-Layer Design (CLD) significantly outperforms standard protocols such as TFRC.

I. INTRODUCTION

Wireless Ad-hoc Networks are infrastructure-less networks of dynamic nodes communicating via wireless links in a multi-hop fashion. Efficiently using the network resources of such networks is challenging. Communicating via shared wireless links raises a contention problem (typically addressed at the MAC layer). The absence of a fixed infrastructure and centralized administration adds a congestion problem where flows or data sessions are typically routed through the same central part of the network. Multi-hop transmissions cause flows not only to interfere with each other but also with themselves.

Working on these challenges in an Oblivious Network Design (OLD), where each problem is separately solved at distinct protocol layers, will not lead to optimal solutions. In order to avoid adverse interactions between optimized network parameters [1], the main network problems need to be combined in a single optimization problem. Based on the tutorials on decomposition and cross-layer optimization in [2] and [3], several works have been published that combine many network parameters into a single Network Utility Maximization (NUM) problem that is implemented in a Cross-Layer Design (CLD). Due to the complex nature of wireless networking, the contention and interference between links, the optimization problem becomes generally nonconvex [4] and [5]. That requires centralized control [6], approximation, and/or complex calculations [5], in some cases the optimization process does not have a polynomial time solution [17]. Several convex utility maximization problems have been published that jointly optimize the congestion and the contention problems [8-11].

We focus on optimizing the end-to-end fair session rates in a bounded queue network in a distributed fashion for multihop wireless networks. Some previous work has been done in this regard [12-15]. In [12, 13], the authors used a stochastic queueing model to estimate the delay and added a constraint in the utility optimization problem. The problem is convex because of the interference model and link capacitance as they solve it for the wired network. The work in [14, 15] will be discussed in more detail in the next section. *We propose a technique to incorporate queue management into the optimization process that solves the congestion and contention problems without adding more constraints, increasing complexity or overheads. The technique acts as an Active Queue Management (AQM) that use the NUM decomposition dual prices to notify the data source about incipient congestion.*

Very few papers provided a practical implementation of their optimization algorithms or discussed the overhead associated with the optimization process [7]. Also, most of the currently proposed algorithms do not explicitly take overheads into account when talking about performance. In this case the results could be misleading. *We evaluate the overhead and signaling associated with the algorithm quantitatively and qualitatively and provide absolute CLD gain values.*

In our previous work [18, 19], we started with the convex utility maximization problem proposed by Yu and Giannakis [10]. We replaced the simple ALOHA module with CSMA and showed the algorithm's gain, robustness, and stability using a custom-built network simulator. *In this paper we use the IEEE 802.11 MAC protocol and implement the optimization framework with AQM in NS-3. The results are compared with a standard TCP-Friendly Rate Control (TFRC) protocol [20].*

Section 2 discusses the related work. Section 3 describes the optimization problem and decomposition with distributed solution. The proposed queue management mechanism is discussed in Section 4. The overhead associated with the algorithm and the signaling method used are discussed in Section 5. Section 6 shows the modifications added to the IEEE 802.11 MAC protocol. The algorithm implementation is explained in Section 7. The simulations and results are provided in Section 8 followed by our conclusions.

II. RELATED WORK

Starting from the network utility maximization framework presented in [21], many researchers developed methods to apply this framework in a distributed fashion. The goal is to solve the problem of congestion as well as contention between nodes in wireless networks, resulting in per-user utilities that maximize the aggregate utility of the network, subject to a specific fairness criterion.

Lee *et al.* [11] developed a distributed optimization algorithm that can find the optimum link rates along with the optimum medium access attempt probabilities of an ALOHA MAC layer in wireless ad-hoc networks meeting specific fairness criteria through a utility function. The algorithm is distributed: every node is communicating with at most its two-hop neighbors to exchange topology information and parameters. The algorithm showed robustness and stability when compared to other similar algorithms [8, 9]. Yu *et al.* [10] extended the algorithm in [11] to

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include the transport layer in the optimization process. They divided the link prices into smaller values to separately represent each session in each link so that the algorithm can optimize the end-to-end session rates instead of the link rates based on a specific fairness criterion.

The objective is to choose the source rates and the link access probability or Transmission Opportunity (TO) so as to maximize the aggregate session utility of all users in the network. The TO is the opportunity given to a node to access the shared wireless medium relative to the rest of the nodes in the same contention area, which is what determines the capacity of each outgoing link of each node. In [10], the TO is the persistent probability of the nodes to access the medium using ALOHA. In [18, 19], we modified and extended the algorithm in [10] to replace the ALOHA protocol with CSMA-CA and provide more robust and stable performance in case of high rates of packet loss and inaccurate topology information. The TO in the case of CSMA-CA represents the transmission probability given to each outgoing link of each node. In order to achieve a different TO for each node, we need to tune the Contention Window (CW) [18]. Tuning the CW has been discussed in several articles to optimize the performance of IEEE 802.11 [23, 24] and recently in [25].

The theory and the mathematical proofs are widely discussed in previous work. Moving from theory to practice in wireless networks raises several issues, especially in wireless ad-hoc networks, that yet have to be considered. These issues are mainly the signaling method, the overhead, and the queue/delay in the network.

- The signaling between nodes has mostly been neglected when evaluating algorithms performance. In [7] and [14] the authors suggested adding the algorithm prices and the required coordination information in the header of the data packets and the acknowledgment packets of the 802.11 MAC protocol.
- The optimizing CLDs with distributed control require a considerable amount of overhead that should be considered when evaluating the algorithm performance.
- The queue length and delay has been considered in NUM [14, 15] but the solutions provided adds more complexity, overhead, and/or requires session-wide knowledge of information that incurs a delay of at least a Round Trip Time (RTT) to learn about and react to queue buildups.

In this paper, we discuss these three issues and provide solutions that are efficient and implementable. We simulate the CLD using a widely used simulator (NS-3) in which we evaluate the signaling efficiency, overhead, and queue/delay in the network. Finally, we compare our proposed CLD solution with a traditional OLD algorithm that uses TCP-friendly Rate Control (TFRC) [20] at the transport layer.

III. THE CONVEX PROBLEM

A. Optimization Model and Decomposition

In our work, we start from the work in [10]. The optimization problem is formulated considering a single channel wireless network, modeled as a directional graph $G(N, L)$ with $|N|$ nodes and $|L|$ logical links. Each link has a feasible physical capacity of C_{max} bps, and S sources transmit at a source rate of r_s bps. $L_{out}(n)$ is the set of outgoing links from node $n \in N$. Each source s emits one flow, using a fixed set $L(s)$ of links on its path, and has a utility function $U(r_s)$. $U(r_s)$ is a concave function and a number of different functions are possible. Here we define it as $log(r_s)$, which aims for proportional fairness among the sessions. Each link $l \in L$ can be shared by a set $S(l)$ of sources. We assume that each node can receive from at most one adjacent node at a time, it cannot receive and transmit simultaneously. Also for a successful transmission, all the nodes in the same contention area should be silent except the transmitter. The nodes in the same contention area are the transmitter, receiver, 1st hop neighbors of the transmitter, and 1st hop neighbors of the receiver. We define the set $N_{CA}(n)$ as the set of nodes in the same contention area of node n, including node n.

The optimization problem is,

$$\begin{array}{ll} \max & \sum_{s \in S} U(r_s) \\ \text{s.t.} & \sum_{s \in S(l)} r_s \le c_l \end{array} \tag{1}$$

where c_l is the link capacity, which is an estimate calculated based on Bianchi's model [16] for IEEE 802.11 according to the following formula,

$$c_l = C_{max} * p_l * B_n \tag{2}$$

where p_l is the link transmission opportunity and B_n is the normalized throughput estimate derived from Bianchi's model.

The utility maximization problem is decomposed into three sub-problems connected by Lagrange parameters (the prices). Two subproblems, addressing the transport layer to optimize the total session rates and the link utility fraction of each session, respectively, follow the same steps as in [10],

$$\max_{0 \le y_s \le 1} (U(r_s) - r_s \lambda_s) \tag{3}$$

$$\max_{\omega \in \Omega} (\textstyle\sum_{s \in S(l)} \lambda_{ls} \, log(\omega_{ls})) \tag{4}$$

where ω_{ls} is the fraction of the rate on link l that is contributed by source session s, $\Omega = \{ \sum_{s \in S(l)} \omega_{ls} = 1, 0 \le \omega_{ls} \le 1 \}$ is the projection operator for ω_{ls}, λ_{ls} is the link-session price that is the Lagrange parameter for sessions s on link l, $\lambda_s = \sum_{l \in L(s)} \lambda_{ls}$.

The third maximization sub-problem addresses the MAC layer. It is a generalization for weighted medium access control [18]. The goal is to optimize the transmission opportunity given to each link in the same contention area so that the total network reward, user utilities, is maximized as follow,

$$\max_{p_l \in \pi} (\textstyle\sum_{\substack{l \in L_{out}(k) \\ k \in N_{CA}(n)}} \lambda_l \, log(p_l)) \tag{5}$$

where $\lambda_l = \sum_{s \in S(l)} \lambda_{ls}$ is the link price, p_l is the transmission opportunity of link l outgoing from node k that is in the contention area of node n, and $\pi = \{ \sum_{k \in N_{CA}(n)} \sum_{l \in L_{out}(k)} p_l = 1, 0 \le p_l \le 1 \}$ is the projection operator for p_l.

B. Distributed Solution

The first two sub-problems (3) and (4) are convex and can be solved in a closed form [10]. Given the link-session prices λ_{ls} of all sessions passing through link l, the optimum link capacity fraction that should be assigned to each session is given by,

$$\omega_{ls} = \begin{cases} \frac{\lambda_{ls}}{\sum_{s \in S(l)} \lambda_{ls}}, & if \ \sum_{s \in S(l)} \lambda_{ls} \ne 0 \\ \frac{1}{|S(l)|}, & otherwise \end{cases} \tag{6}$$

where $|S(l)|$ is the number of elements in $S(l)$.

The third sub-problem (5) is similar to (4) for which we can use a similar solution. Given the two hop neighbors' prices, i.e. prices belonging to the nodes in the same contention area with node n, we can derive p_l as follows:

$$p_l = \begin{cases} \frac{\lambda_j}{\sum_{\substack{j \in L_{out}(k) \\ k \in N_{CA}(n)}} \lambda_j} & , \; if \; \sum_{\substack{j \in L_{out}(k) \\ k \in N_{CA}(n)}} \lambda_j \neq 0 \\ \frac{1}{\sum_{k \in N_{CA}(n)} |L_{out}(k)|}, & otherwise \end{cases} \quad (7)$$

The node transmission opportunity will be given by

$$P_n = \sum_{l \in L_{out}(n)} p_l \quad , \quad n \in N_{CA}(n) \quad (8)$$

There is only one price that needs to be updated, the link-session price. They are updated according to the following formula,

$$\lambda_{ls}^{k+1} = [\lambda_{ls}^{k} + \beta \left(\log(r_s^k) - \log(\omega_{ls}^k * c_l^k)\right)]^{+} \quad (9)$$

where c_{ls}^k is the link capacity of the session $s \in S$ in the link l in iteration k, and β is the step size.

IV. QUEUE MANAGEMENT MECHANISM

Our queue management mechanism has the same fundamentals as the work of Qiu *et al.* [14] but with a more localized, simpler implementation, and less overhead. We start with our previous work in [18], which is a convex optimization problem (1). After decomposing it as described, the resulting sub-problems can be implemented in two different layers, the first one maximizes the network utility by maximizing the session rates with proportional fairness at the transport layer. The second one optimizes the sessions' share on each link, implemented at the link layer. The third sub-problem, which is concerned with the queue management, works on the contention between nodes to access the medium at the MAC layer. The goal of the second sub-problem is to find the optimum TO (p_l) for each outgoing link l in each node n and set the suitable link capacity according to (2).

In order to incorporate the Queue management in the optimization process, unlike [14] and [15] that are looking at the end-to-end average delay of each session, we look at the individual queue of each node in the session path and deal with each one locally. If the queue builds up in any of the nodes in the path of the multi-hop session, it means that the capacity estimate of that specific link is not correct. That could happen due to various reasons, especially in wireless ad-hoc networks. For example, if parts of the network, parts of the sessions' paths, are exposed to an unexpected high level of noise, the received signal will have a low signal-to-noise-ratio and could be neglected by the receiver. In case of the IEEE 802.11 MAC protocol, the transmitted packet will be retransmitted several times until an acknowledgment is received or packet dropped. That will lead to queue buildups in the noisy areas. We interpret that as a degradation of the link capacity. In our proposed solution, we adjust the algorithm-estimated link capacity by a queue-length-based Factor (QF). The new adjusted capacity c_{l_Q} is calculated as follows,

$$c_{l_Q} = C_{max} * p_l * B_n * QF_n, \; l \in L_{out}(n) \quad (10)$$

$$\text{where} \quad QF_n = e^{-\frac{1}{Z}\left(\frac{q_n}{Q_{n_{max}}}\right)^2} \quad (11)$$

and q_n is the queue length at node n, $Q_{n_{max}}$ is the maximum queue length at node n, and Z is the aggressiveness factor.

The Queue Factor throttles the estimated capacity seen by the optimization algorithm. Reducing the link capacity will directly affect the link price of that specific link according to (9). The throttled capacity will increase the link-session price, hence it increases the link price, session prices, and node price. The session price increases will lead to lowering the rates of all the sessions that are using this link, hence fairly sharing the reduction in utilities. Furthermore, the increase in the node price will lead, according to (7) and (8), to redistributing the TO among the node in the same contention area which, in turn, leads to providing more access opportunity to the node with longer queue length. The aggressiveness factor (Z) is used to provide different capacity throttling aggressiveness for different delay requirements in the network.

This mechanism uses the prices that are already available in the CLD. Therefore, we avoid the need for a different type of prices or special control signaling. Also, in this CLD there is only one price that needs to be updated and communicated between layers and nodes. The work in [14] and [15] needs to collect data along the session path, so that each session link has information about the delay prices the remaining links used by the same session. This information should be collected before any decision can be taken about the delay and queue buildups. Our mechanism acts based on the local queue information first, then the prices propagate to the source nodes and the neighbors to re-assign utilities in a fair manner.

V. SIGNALING AND OVERHEAD

Every active node contributing to the optimization process, as session source, destination, or relaying node, has to send signaling information (overhead) periodically. Normally, two types of information transmissions required. The first one is broadcasting, to propagate prices to the first and second hop neighbors. The second one uses point-to-point transmissions that send the session prices forward and backward along the session path.

The work in [14] added the information to the header of the data packets, in order to deliver the information to the neighbors and the nodes in the session path upstream. The information are also added to the acknowledgments to deliver the information downstream the session path. In [7], the information was added to the RTC/CTS packets of IEEE 802.11 for quick delivery.

In order to keep our proposed CLD solution modular and compatible with the global standards, we defined a separate control message to carry the information required. We combined all the coordination and update information required by the algorithm in only one control message, so that we avoid the need for point-to-point message transmission. The message is broadcasted from every active node to its first hop neighbors. The information in the message broadcasted by node n are the node price P_n, the first hop neighbors' prices NP_n, and the hops prices HP_s of each session $s \in S(n)$ passing through node n. The size of the message M_n broadcasted from node n is equal the number of prices carried multiplied by the size of the price in bytes P_{bytes} as follows,

$$|M_n| = \left(1 + |NP_n| + \sum_{s \in S(n)} |HP_s|\right) * P_{bytes} \quad (12)$$

The dedicated message is a key in developing a standalone protocol. The CLD does not depend on the routing protocol in collecting the information about the neighbors. This makes it compatible with any routing protocol and suitable for different applications. Moreover, the option to add the information in the RTS/CTS packets is applicable for specific purpose applications that can be evaluated in future works.

The overhead is also considered in the optimization process. The overhead is monitored at the MAC layer and estimated using a moving window average method. At each iteration, after the link capacities are calculated, the overhead rates are subtracted from the link capacities, and then the algorithm continues its iterations until it converges. With each iteration, the transmission opportunities are adjusted for the nodes and the links considering the amount of subtracted overhead rates, so, the overhead rate is included in the optimization and the fairness calculations.

VI. MODIFIED IEEE 802.11 MAC

The optimization algorithm assigns the available resources fairly among the sessions. The capacity, as one of the resources in the network, is limited by the throughput that can be achieved by the MAC layer. The algorithm assigns the resources by providing the optimum access opportunity that should be given to each node.

Bianchi's model [16] accurately estimates the throughput of IEEE 802.11 with basic and RTS/CTS access mechanisms. The estimated value will be calculated based on the optimum saturation throughput of the MAC layer settings. [23] and [24] optimized the IEEE 802.11 MAC throughput by tuning the CW which affect the transmission probability for each node to achieve fairness with higher throughput among the contending nodes. But these values consider only fairness and throughput at the MAC layer, while the CLD optimizes for end-to-end session fairness and throughput.

In [16], the optimum throughput achievable is shown to be independent of the number of nodes contending for access to the medium. We used these optimum throughput values as an upper limit for the expected link capacities of the contending nodes. Then using (10), the capacity will be estimated using the algorithm's calculated transmission opportunity. The CW of each node will be tuned according to the following widely-used formula [16, 23, 24, 25],

$$CW_n = \frac{2}{P_n} - 1 \qquad (13)$$

where P_n is the node transmission probability.

That leads to an aggressive transmission as we assume optimum throughput all time. This will keep the network saturated and maximize the aggregate utilities. If there are any queue buildups due to overestimated capacity, the queue management mechanism will reduce the capacity seen by the algorithm and the session rates will go down until a balanced state is reached in the network.

VII. IMPLEMENTATION

Our CLD can be implemented without alleviating the boundaries between network layers and with minimal effect on the other network protocols. The CLD is divided into sub-modules that can be separately implemented in each layer. The modules communicate with each other to exchange prices. Each layer takes its own decisions based on the prices.

The distributed implementation of our CLD is given in Table 1 with a separate function for each layer. The algorithm convergence condition can be set based on the application, topology change, and/or network size. In general, we consider that the algorithm converged if there is no change in the calculated session rates after a certain number of iterations.

TABLE 1. DISTRIBUTED IMPLEMENTATION OF THE CLD.

	MAC layer	***Transport layer***
0	*Initialize the algorithm* *Set the initial link-session prices = 10;*	
1	*Calculate the algorithm prices*	
	- Calc. Outgoing links prices *- Calc. Sessions fraction (6)* *- Calc. Node price*	*- Calc. Sessions price*
2	*Calculate the rates*	
	- Calc. Links rates	*- Calc. and set sessions rates*
3	*Calculate the Transmission probabilities* *For the outgoing links (7) and the nodes (8)*	
	- Tune CW (13)	
4	*Estimate Link Capacity*	
	- Calc. The QF (11) *- Calc. Bianchi's throughput* *- Estimate the Overhead rate* *- Calc. adjusted capacity (10)*	
5	*Update the link-session prices (9)*	
6	*If the algorithm converges* *- end* *else* *- wait for 1 second* *- Broadcast update message with node and sessions prices* *- Go to 1*	

VIII. SIMULATIONS AND NUMERICAL RESULTS

Using NS-3, the networks simulations are carried out for our CLD and TFRC [20] under the same conditions. In both cases, the PHY uses direct-sequence spread spectrum (DSSS) with 1 Mbps physical link capacity. The transmission range is set to 100m and the carrier sense range to 200m. The routing is not the focus of this paper so we used static routes for all scenarios. The simulation runs for 200 seconds. For consistency, each value of the following results is an average of 10 values resulted from running the same scenario 10 times with different random number seeds, that will change the back-off times and the transmission jitter in each node. The default value of the QF parameter Z is set to 0.1, different values of Z are discussed later.

The experiments are conducted under three network configurations, (*a*) symmetric, (*b*) randomly overlapped flows, and (*c*) long/short flows with bottleneck node as depicted with their flows in Fig. 1. In (*a*), each node sends one session to the center node *X*, except node *A* that sends two simultaneous sessions to *X*. (*b*) and (*c*) have bottlenecks at node *C* and a range of session with different lengths.

Figure 2 shows the throughput of the different sessions for the three topologies. For topology (*a*), with symmetric interference between nodes, all sessions achieved nearly equal rates, even the first and second session that are generated from the same source. On the other hand, TFRC cannot provide fair rates for the first two sessions as it is bounded by the MAC layer fairness. For general topologies (*b*) and (*c*), we can see that CLD provide higher throughput and better fairness among different session lengths. The shortest session (no. 2) in (*b*) and the longest (no. 3) in (*c*) have proportionally fair rates not much higher or lower than the rest of the sessions in the same topology.

Table 2 shows the numerical average of different network measurements. The fairness among the sessions at their sources and destinations are calculated using Jain's fairness index. The

CLD fairness at the transmitters' side shows that the proportional fair rates set by the algorithm are higher than 0.99. The fairness among the sessions at the receivers' side can be lower due to uneven packet losses, congestion, and delays. But the CLD fairness at the receivers' side still reaches a fairness index of 0.99 even in a random asymmetric topology with different session lengths.

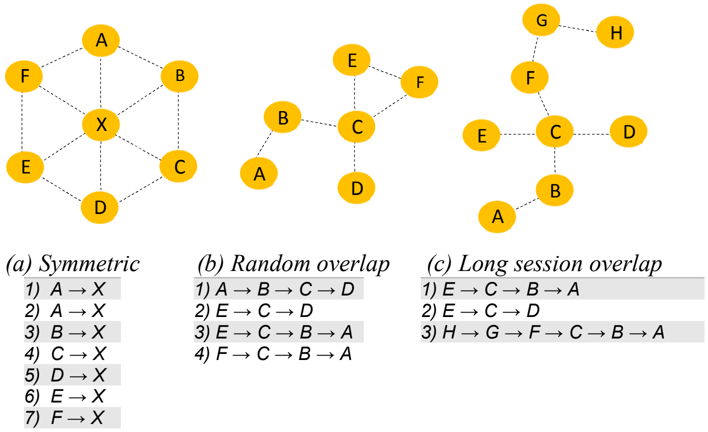

Fig. 1. Experimental wireless network topologies.

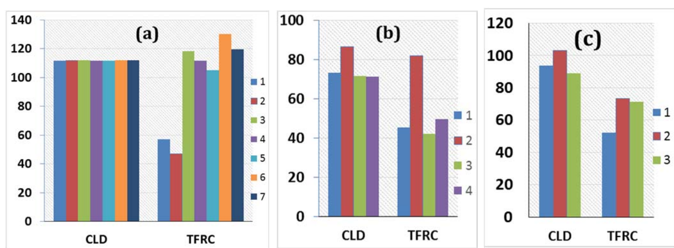

Fig. 2. The throughput of each session.

TABLE 2
COMPARISON RESULTS CLD VS. TRFC FOR THREE TOPOLOGIES

	(a) CLD	*(a)* TFRC	*(b)* CLD	*(b)* TFRC	*(c)* CLD	*(c)* TFRC
Jain's fairness (transmitter side)	**0.99999**	0.84959	**0.99335**	0.84513	**0.99557**	0.87547
Jain's fairness (receiver side)	**0.99999**	0.83278	**0.99293**	0.83934	**0.99628**	0.84651
Delay (mSec)	**14**	2115	**439**	3664	**1210**	3982
Packet loss (%)	**0.13**	8.39	**0.35**	14.19	**0.08**	16.67
Total throughput (Kbps)	**782.8**	688.7	**303.6**	219.35	**285.7**	197.0
Overhead (Kbps)	**3.55**	8.88	**3.94**	12.49	**4.83**	11.20
Total Utilities	**14.34**	13.76	**7.51**	6.89	**5.93**	5.44

Due to the capacity estimate and active queue management, the average delay in the CLD network can be reduced around 150 times in single-hop transmissions in topology (*a*) and at least 3.3 times in multihop sessions with different lengths. The CLD average packet loss percentage is also 40 times lower than TFRC due to the same reasons. The average throughput values show that the CLD can provide 38% and 45% extra throughput, to the networks (*b*) and (*c*) respectively, by coordinating the work of the MAC layer with the transport layer. The overhead required for CLD coordination is less than half the TFRC's overhead in all cases. With the less overhead, the CLD can provide an additional 45% throughput in the long session topology (*c*). The CLD overhead rates in (*b*) and (*c*) are a function of the number of neighbors and the number of session hops based on (12). The TFRC overhead rate depends on the number of session hops and the feedback report update rate. The overall average CLD utility, which is the aggregate log rate of the sessions, is higher than TFRC in all cases. This is achieved at the same time the approach results in much lower average delay and packet losses.

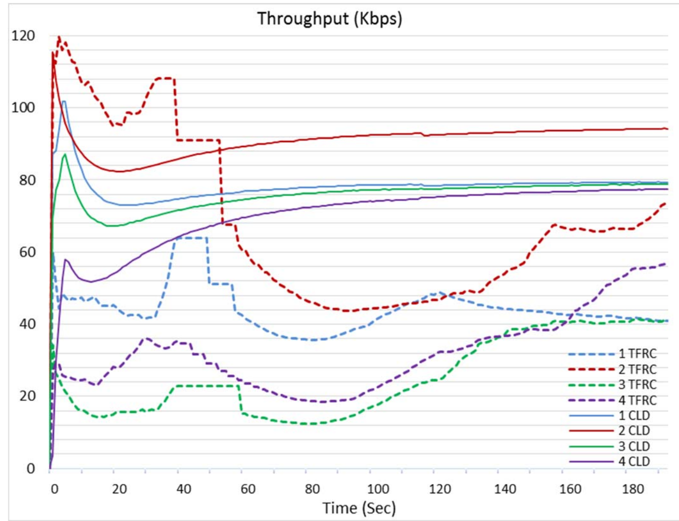

Fig. 3. Throughput convergence of topology (b).

Figure 3 shows the throughput rates of each session in case of random topology (*b*). These values are results of a single seed simulation, not an average. The CLD rates converge directly to the optimum rates from any initial point (i.e. any initial prices). The very small turbulences in the CLD (solid lines) between times 100 and 120 seconds are due to the QF adjustments happening during convergence. TFRC adjusts its rates after each packet loss and feedback report received, resulting in many peaks and valleys during operation.

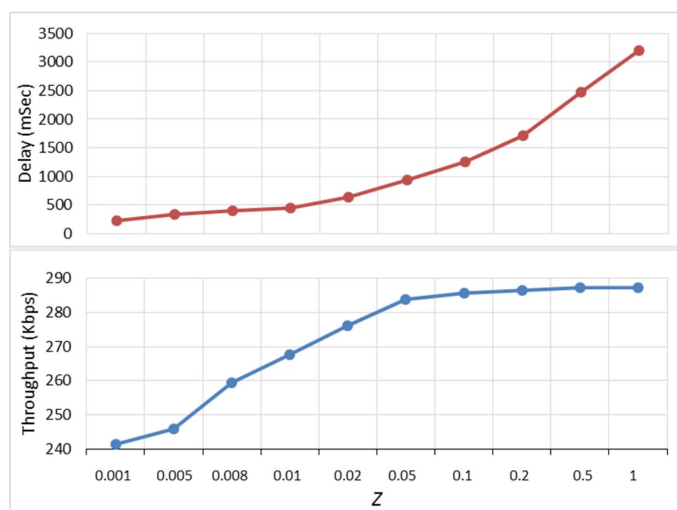

Fig. 4. The effect of aggressiveness parameter Z on network average delay and throughput.

The effect of the aggressiveness parameter Z on the network average delay is shown in Fig. 4 along with the resultant average throughput for network (*c*). Lowering the Z value tends to sharpen the decaying QF in (11) that throttles the link capacity as soon as the queue starts to building up. On the other hand, lowering Z will also lower the total throughput in the network due to lower capacities and rates.

IX. CONCLUSION

The proposed localized queue management mechanism can guarantee a stable network with bounded queue length and delay without increased overhead or additional control signaling. The proposed CLD along with the queue management mechanism works in a distributed fashion without alleviating the boundaries between network layers. The NS-3 simulations show that the CLD can coordinate between network layers and network nodes to provide very high fairness between end-to-end flows, surpassing 0.99. It also increases the total throughput up to 45% while reducing the network average delay at least 3.3 times with less than 0.4% packet loss, as compared with TFRC.

Starting from these promising results, the future work is to introduce mobility to test the algorithm performance in case of dynamic topologies. The results to-date (see Fig. 3, for example), seem to indicate that our proposed scheme converges quite fast, so we expect that it will work well in case of any disruption, session path changes, and node disappearances. We are also considering how to integrate the routing in the optimization process, where prices may be used to guide the selection of appropriate paths.

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