

Cross-Layer Mixed Bias Scheduling for Wireless Mesh Networks

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Abstract—In this paper we propose a mixed bias approach which makes use of cross layer optimization. The cross-layer parameters are based on conditions in the network from multiple layers and are used to determine resource and time allocation for nodes in the network. Unlike existing proposals, we propose to bias against several parameters such as link quality and queue size in addition to node distance. We also propose a combined mixed bias approach which takes into account multiple parameters together. The scheme is evaluated using simulation experiments. The performance results are reported in this paper.

Index Terms—Resource Allocation, Scheduling, Wireless Mesh Networks, Mixed Bias

I. INTRODUCTION

WIRELESS mesh networks (WMNs) have been increasingly deployed as a backbone solution for many network applications. However, WMNs still suffer from scalability, poor end-to-end throughput and QoS problems [18]. However since WMNs consist of mesh routers (MR) which often have greater resources (CPU, memory), they are useful in solving some of these problems via scheduling by taking some of the computation burden off other nodes [8].

Many scheduling solutions focus on biasing against only one characteristic of the network which is detrimental to scheduling or throughput [4,7,16]. While this limitation allows for simpler cross-layer solutions, it is preventing the approaches from reaching their full potential. This is often true regardless of whether the scheduling scheme is hard-fairness, max-min or proportional. For example [7,8,9] focus on preventing links from interfering in order to improve the scheduling by adjusting the transmission power of the nodes. The proposal in [16], gives preference to nodes which are close to each other when scheduling. However, in order for a scheduling algorithm to be effective and flexible in many situations it may be beneficial to try to capture many characteristics in one scheduling algorithm. Cross-layering allows the algorithm to gain information from many layers which normally cannot be available in one layer. Instead of just optimizing with respect to one network characteristic, it may be possible to take techniques from many approaches and optimize jointly. In our approach, we propose a cross-layer, mixed bias scheduling algorithm for wireless mesh networks.

The cross-layering will provide information on link-quality and distance between nodes. Link quality will be provided from the physical layer while distance can be provided in many ways. Distance could be computed by the number of hops between two points, by measuring the delay or by using real life coordinates if the nodes are equipped with Global Positioning Systems (GPS). In this work we use the number of hops. A portion of the scheduling resources will be biased according to a set of heuristics that penalize nodes for various “bad behaviors” such as distance from the gateway, overuse of traffic, poor link quality and so on. Each heuristic will be assigned a different proportion of the network resources which will be determined experimentally. Another portion of the resources will be left for absolute fairness in order to ensure that none of the links are starved and that some minimum level of service is maintained. Then the collective system will be optimized to produce what we expect to be a high throughput fair scheduling for wireless mesh networks.

This paper makes three main contributions: First it provides a more generalized mixed-bias technique which may be applied to other network characteristics such as queue-size and link quality in addition to distance. Second, it presents a combined mixed-bias approach which aggregates many characteristics from multiple network protocol stacks into one technique. Finally, the paper provides the performance evaluation of the proposed schemes.

The remainder of the paper will be organized as follows: Section II presents background and related work. Section III presents the proposed mixed-bias scheduling techniques. Section IV presents the simulation environment and discussion of the simulation results. Finally, Section V concludes the paper and discusses future research directions.

II. BACKGROUND AND RELATED WORK

Scheduling in wireless networks is often a problem of the link layer or MAC specifically. However in this layer, there is often not enough information available to make an informed decision on which nodes should be allowed to transmit at a given time or which nodes should be allocated more resources. Information such as queue lengths, channel quality and distance to destination may be available from other layers. This information would be helpful in making more accurate decision on how to allocate time and resources to nodes.

In [17] the authors identify end-to-end delay and fairness as important performance characteristics. These characteristics are affected by metrics such as jitter, aggregate throughput, per-node throughput and packet loss ratios. We propose to extend this idea by making use of metrics which are measured at various layers to provide feedback for scheduling and resource allocation algorithms. [18] Identifies the MAC as imperfect and an area that would benefit from cross-layered design. The best-effort design of many current MAC implementations is insufficient for dealing with congested networks which is often the case in real world deployments.

III. THE PROPOSED MIXED BIAS SCHEDULING SCHEME

A. Motivation behind Mixed Bias Approach to scheduling

In [16], it is argued that a fraction of the total resource allocation should be strongly biased against long connections while the rest remains allocated in a fair (max-min), or weakly biased manner (proportional fairness). In their proposal they make use of only two different scheduling schemes in their mixed-biasing. The approach that will be taken in this paper, however, is that by using more than two different scheduling approaches, more could provide even greater utilization of network resources. For example, in the original Mixed-bias approach, only the long connections (as in number of hops) are biased against. It was demonstrated that even while biasing against the long connections, the decrease in performance for those connections was similar to proportionally fair solutions. At the same time, because of the biasing, the short connections benefited greatly. It is also possible, however, to bias against greedy connections, poor quality connections or any other metric. Then as a whole this entire system of biases could be optimized together to maximize both the fairness of the scheduling and the throughput of the network.

In our approach, we make use of mixed-biasing to enhance our previous work which was an STDMA scheduling for wireless mesh networks [6]. The same approach can also be implemented in a network using an IEEE 802.11 distributed co-ordination function by giving preference in the MAC layer queues to the flows which have the least bias against them. The mixed-biasing is expected to improve the throughput of the network while maintaining some degree of fairness due to some of the network resources being allocated in a fair manner. As opposed to just biasing against long connections, however, our approach will bias against other factors using a heuristic approach. In our approach we will represent the capacity of the network, C as in Equation 1.

$$C = \sum_{i=1}^n (\gamma_1 f_1 + \gamma_2 f_2 + \dots + \gamma_i f_i + \dots + \gamma_n f_n) = 1 \quad (1)$$

$$\sum_{i=1}^n \gamma_1 + \gamma_2 + \dots + \gamma_i + \dots + \gamma_n = 1$$

Where C is the total capacity of the network

$\gamma_1, \gamma_2 \dots \gamma_i \dots \gamma_n$ are the weight of a given biasing scheme

$f_1, f_2 \dots f_i \dots f_n$ are the biasing functions for particular characteristics

In this general case, any number of biasing function schemes may be applied which may result in a fine grained tuning of the network against specific biases. If starvation is to be avoided and some level of fairness ensured, at least one function must not bias against any node or flow but give “hard fairness”. Also the associated weighting scheme for this function must not be zero. The weighting could be either static or dynamic. For example in a dynamic implementation each weight may be allowed to shift between pre-determined ranges depending on the utilization of the network. For example one may let γ_1 shift from a weight of 0.25 to 0.5 depending on the utilization of the network or some other parameter.

Since it is already well established that proportional fairness, max-min fairness and mixed-bias scheduling applied to one characteristic at a time is an effective technique [4,7,16], we propose that there exists some combination of scheduling techniques which will also result in good performance. In this paper we provide experimental confirming of this hypothesis.

B. Description of the proposed biasing parameters

In this section, we present for biasing techniques. The first technique is adapted from [16]. This technique uses mixed-biasing to bias against the distance from the gateways. This technique is important because the farther away from the GW a MR is, the more hops the packet must traverse to arrive at the GW. This means the probability of a successful delivery decreases as the MRs are farther away from the GW. Thus if we allow fewer packets from the farthest gateways, we will achieve higher throughput overall. However, at the same time, as the packets move closer to the GW successfully, there is a greater chance they will arrive since the closer MRs are given preference. Since the closest MRs to the GWs must handle their own MCs as well as the traffic from the farther MRs they should be allowed to have extra resources to handle this extra requirement.

The second technique favors MRs with full queues, and thus biases against those with shorter queue length. This is important because if we can give some preference to these routers, perhaps fewer packets will be dropped by reducing the frequency with which the queue is full. By giving preference to full queues, we let the near empty queues build up and at the same time, allow the extremely full queues to empty. This results in balancing of all the queues in the network. If we can reduce the number of dropped packets, the delay will likely also fall significantly since the overhead in resending a packet is often quite large. This is especially true in multi-hop networks such as WMNs since the retransmission control packets must also traverse the multiple hops.

The third technique biases against poor links. This technique is important because link quality may change often depending on objects blocking signals, environmental

conditions that may make certain links in the network perform better than others. When we bias against these links, we give preference to those links which are performing well and allow them to transmit more, thus increasing the overall packet delivery ratio.

In each of the first three techniques, resources assigned to a node are determined using Equation 2. For each approach, the particular characteristic is biased against using a measure taken from a specific network layer. The information is then used at the MAC layer to help compute the scheduling or resource assignment.

$$R = \frac{\alpha}{c^{\beta_1}} + \frac{1-\alpha}{c^{\beta_2}} \quad (2)$$

Where R is the resources allocated to the node
 c is the measure of a particular characteristic, $c > 0$
 α is the weight for each bias technique, $0 < \alpha < 1$
 β_1, β_2 are the biasing constants that determines the strength of each bias, $\beta_1, \beta_2 > 0$

The last technique is the combined mixed-bias approach. In this approach several mixed-bias techniques are combined to form one all-encompassing scheduling algorithm which allows preferred access to only those MRs which exhibit all of the qualities of a preferred MR. The criteria of which MRs are preferred are completely up to the network administrator and could even be modified dynamically. For example under certain conditions or applications, more or less characteristics could be factored into the combined mixed-bias formula. It is expected that the more characteristics we use at one time, the more complete of a picture of the network we receive and thus we are able to make a more informed decision on how to schedule access to the MAC layer.

It should be noted that for all of these techniques, there are two different approaches that could be applied when deciding on transmission scheduling. (i) A centralized approach that could be taken if the gateway is controlling the scheduling (such as in the STDMA scheduling from the fair scheduling with multiple gateways approach) (ii) A distributed technique where each MR itself decides whether to send the packet at a given time or to hold off on sending and give the opportunity to send to another MR. This technique relies on the assumption that all MRs in the network will co-operate, which is not always the case. Despite this weakness, the lack of a central authority removes the single point of failure problem. It is up to the network designer / administrator to decide on which technique is best for the particular application or network.

C. Biasing against distance from the gateways

In our approach for biasing against distance, we follow the same approach as [16], which forms the basis for much of this work. In the original approach, there is no concept of gateways but rather an ad-hoc network with a random source-destination traffic model. It is shown that the original mixed-bias provides increased performance compared to both max-min and proportional fairness if a stronger bias is applied to

nodes which are far away from each other while at the same time applying a weaker bias so that there is still limited service to the non-preferred nodes. This is different from other scheduling algorithms because in other solutions, some nodes are starved while others receive all of the resources. Avoiding starvation is important problem to consider in WMN design especially since factors such as interference fading and other factors already contribute to low reliability in WMNs [15]. If the problem of starvation can be reduced, the reliability of the network will increase significantly. In the mixed-bias approach there are two different biases, one with a factor of 5 and one with a factor of 2. The latter is similar to proportional fairness. There is also a factor of weighting between the two competing schemes of 0.5, which splits the amount of resources given to each scheme evenly. We make use of the same parameter values in our approaches to allow for easy comparison.

In our system model we are applying a similar technique to a WMN which has random source and one gateway as a destination. Unlike the proposal in [16], we introduce the concept of a gateway making the network model closer to that of WMN and less like a wireless ad hoc network. For this technique there are several ways in which the distance between the nodes could be computed. If each node had GPS capabilities, the distance could be easily computed whenever necessary by an additional query within a RTS packet. Alternatively, TTL counts or hop counts from higher layers could be used to determine the distance in hops between nodes and a table of known distances could be built up such that each node would know roughly how many hops it is away from the GW.

D. Biasing against low demand (queue size)

Here, we bias against MRs which have little data queued to be transmitted. By doing this, the MRs with longer or nearly full queues have the opportunity to clear space for incoming traffic rather than dropping packets. At the same time, MRs with more rooms in their queues have the ability to hold onto them until there is more data to send all at once. Of course this technique will not work well when the entire network is completely congested. Like biasing against the distance, we propose to split the resources available to this scheme in half, and bias proportionally (factor of 2) and strongly (factor of 5) against the queue size. The queue size that we are referring to for this technique is the MAC layer queue. In this technique, we use the inverse of Equation 2 because we want to give preference to those nodes which have the largest queues. This means that we waste less time giving resources to those nodes which do not have much to transfer in a given time. The mixed-bias technique, however, still gives some priority to those nodes which do have a small amount of traffic, so it will prevent starvation of these nodes.

E. Biasing against poor link-quality

The reason for biasing against poor link quality is again to try to reduce dropped packets and end-to-end delay. Link

quality would be determined using a signal to interference plus noise ratio (SINR) similar to [4] or packet error rate (PER) from [10]. This value would help us determine how many resources to allocate to a node using this value as c in Equation 2. When we avoid links with poor quality by waiting for the link to hopefully improve, we allow links which are nearby with higher link quality to transmit more packets. This may give the link the opportunity to improve in quality. If the link doesn't improve in quality, at least it is getting fewer opportunities to send packets, so the poor service the users will experience is related directly to the quality of their own link and does not negatively affect the rest of the network. In other schemes this might not always be the case. The poor quality link may try to communicate as if the link were behaving normally. Again we use the same biasing parameters in this scheme with a proportional bias (factor of 2) and a strong bias (factor of 5) mixed together.

F. Combined Cross-Layer Mixed-Bias Scheduling and Resource Allocation

Lastly, our combined mixed-bias technique is novel. It takes all of the mixed-bias techniques outlined previously and combines them into an all-encompassing technique which considers multiple characteristics of the WMN at once. This technique provides a more complete snapshot of the network at a given moment for the MR to make a more informed decision on its state. Rather than just looking at one characteristic as [16] did the combination of characteristics provides a more general solution which is more flexible and useful in a wide variety of environments and applications. This combined mixed-bias approach is similar to the cross-layer solution from [5] except our approach is for scheduling instead of routing. Also our approach uses mixed-biasing which is quite different from the simpler metrics used in [5]. The key to the combined mixed-bias technique is providing a fraction of the resources to each of the mixed-bias techniques. For example, half the resources could be assigned to the distance technique while a quarter could be assigned to queue length and the last quarter to link quality. The network designer or administrator could specify these quantities manually. In a more complex network, these parameters could dynamically change depending on which applications are being run on the network at a given time or what the environment around the network is like. The combined mixed-bias scheme is shown in Equation 5.

$$R = \gamma_1 R_1 + \gamma_2 R_2 + \gamma_3 R_3 \quad (3)$$

Where R is the resources allocated to the node

R_1 is the resources calculated using Eq. 1

γ_1 is the weight of scheme 1 in the combined biasing

R_2 is the resources calculated using Eq. 2

γ_2 is the weight of scheme 2 in the combined biasing

R_3 is the resources calculated using Eq. 3

γ_3 is the weight of scheme 3 in the combined biasing

$\gamma_1, \gamma_2, \gamma_3 > 0$ and $\gamma_1 + \gamma_2 + \gamma_3 = 1$

In Eq. 3 the gamma variables range between 0 and 1 and are used to assign a proportion of the resources to a given scheme. These may be assigned by the system designer. Alternatively, these values may be assigned dynamically if a cognitive or adaptive system is being implemented.

IV. DISCUSSION OF THE EXPERIMENTAL RESULTS

We have used NS3 [12] as a simulation tool in the performance evaluation. NS3 is the successor to the most popular network simulation tool for wireless networks, NS2 [11]. In our experiments, we analyze the performance of the proposed approaches with respect to two metrics. The first metric is packet delivery ratio (PDR). This is computed by the ratio of the successful packets against the total packets. The second metric we use to evaluate the performance of a scheme is average end-to-end delay. The average end-to-end delay is computed by adding the delay from source to destination along the path a given packet takes from source to destination.

The simulation experiments on the cross-layer mixed-bias scheduling were performed using the NS3 simulation environment. NS3 provides an environment which allows for straightforward implementation of wireless MAC layer protocols.

In this section we will discuss the performance of cross-layer mixed-bias scheduling techniques. In our performance evaluation we evaluate IEEE 802.11 MAC against three mixed-bias techniques. The first technique is mixed-bias against distance (M-B Distance) which is comparable to the approach given by [16]. The second technique is mixed-bias against queue length (MB Queue Size) and the third is a combined mixed-bias approach (Combined M-B) which is mixed-bias against both distance and queue length. The routing algorithm used in each case is the Optimized Link State Routing (OLSR). We investigated the effect of number of mesh routers, gateway and traffic flows on the network performance.

A. Effects of number of mesh routers

In Figure 1, the effects of varying the number of MRs on the average end-to-end delay is evaluated. In this experiment the network had two flows and a single GW. The highest delay is the worst performing, and in this case the best performing approach was the combined mixed-bias approach. This is an important result because, while the combined approach may not always result in the highest packet delivery ratio (Figure 9) it does give a low delay. This tradeoff may be worthwhile; however, the time it takes for retransmissions is also important in the case where packets are dropped. The difference in delay between some solutions is significant. For example, with 25 MRs, there is double the delay using the IEEE 802.11 approach, compared with the combined mixed-bias approach.

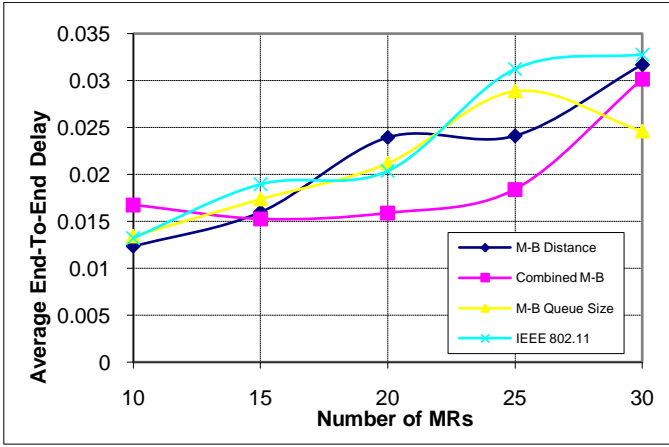


Figure 1 Average End-To-End Delay, Two Flows

Figure 2 shows the effect of varying MRs with respect to average end-to-end delay. In this experiment there are five flows and a single gateway. One interesting result here is the mixed-bias distance approach. When the network size grows large (30 MRs), the delay increases dramatically compared to the other solutions. This means for larger networks, the approach in [16] alone may not be suitable. This is where the combined mixed-bias approach becomes an attractive option. The extremely poor delay result for the mixed-bias distance with 30 MRs also suggests that in this situation, when using the mixed-bias combined approach it may be best to assign more resources to the queue-size rather than an even split. Here we still have comparable packet delivery ratios while still retaining low delay. The exponential increase in the mixed-bias distance approach may be attributed to the increasing number of average hops between the gateway and mesh routers. Since there is only one gateway in this experiment and the mesh routers are increasing, the distance from the gateway grows as the number of mesh routers grows. Since we are biasing against only distance, the farthest nodes suffer the most and thus the average delay increases.

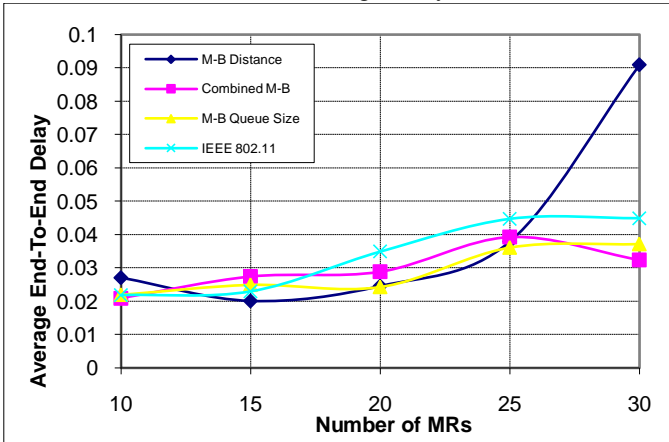


Figure 2 Average End-To-End Delay, Five Flows

B. Effects of number of gateways

In Figure 3, the effect of varying gateways against packet delivery is shown. In these results we can see that again the mixed-bias approaches perform the best, however, not by very

much. The fair scheduling approach performs similarly to the mixed-bias approach but still slightly fewer packets are delivered. When there are fewer gateways the combined mixed-bias approach performs slightly worse than the other two mixed-bias approaches which suggests a different combination of weightings may be more effective. For example with one gateway, the best performing mixed-bias approach was the queue size so in this situation it may be best to give more resources to this approach rather than an equal split.

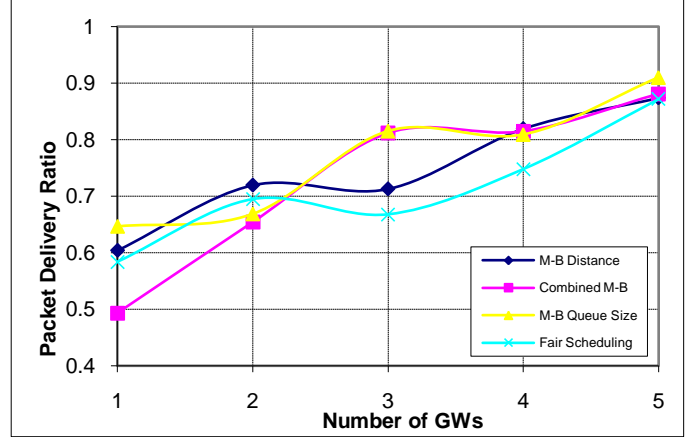


Figure 3 Average Packet Delivery Ratio, 250 Clients, 50 MR

In Figure 4 we compare the effect of varying gateways to the average end-to-end delay. One interesting result is the combined mixed-bias approach, which performs poorly compared to the others when there is only one GW. This result suggests that the combined mixed-bias approach is affected by the bottleneck introduced when using a single GW, while the other approaches are not affected as much.

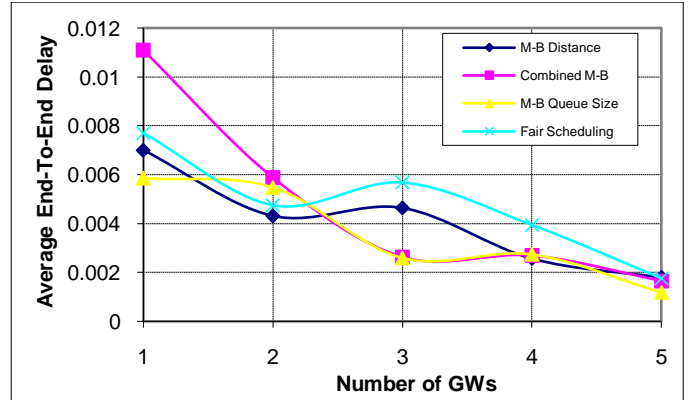


Figure 4 Average End-To-End Delay, 250 Clients, 50 MR

C. Effects of number of traffic flows

In Figure 5 we compare the effect of varying the number of traffic flows on the average PDR. These results were obtained with a network size of 30 MRs and a single GW. As the number of flows increase the performance of the network in all cases drops significantly. In almost all cases, the mixed-bias approaches perform as well or better than the IEEE 802.11 approach. The exception is with four flows where the IEEE 802.11 approach performs slightly better than the mixed-bias approaches. The reason for this may be that a

maximum is being reached in the IEEE 802.11 approach. When the number of flows is increased again to five flows the PDR drops significantly which indicates that a maximum may have been reached with the IEEE 802.11 approach.

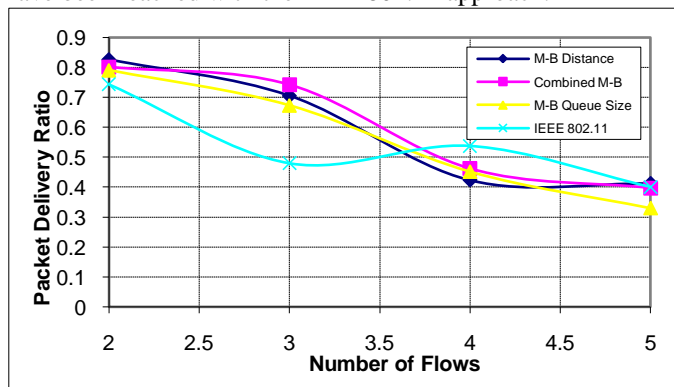


Figure 5 – Packet Delivery Ratio, Varying Flows

D. Summary of Cross-Layer Mixed-Bias Scheduling Results

In summary, the mixed-bias approaches we proposed performed well with respect to the performance metrics. Often the mixed-bias approaches performed as well or better than the IEEE 802.11 MAC in terms of packet delivery ratio. In terms of average end-to-end delay the mixed-bias approaches consistently performed better. These results provide validation that the mixed-bias approach is a promising approach to explore in greater depth. Particular the combined mixed-bias approach which performed as well as all of the other mixed-bias approaches. With further tuning of the biasing parameters it is expected that even better performance can be obtained.

V. CONCLUSIONS AND FUTURE WORK

In this paper we proposed and evaluated variations of mixed-bias approaches. These approaches have also been compared with the original mixed-bias distance approach and against IEEE 802.11 MAC. Our proposed mixed-bias queue size approach performed better than the mixed-bias distance approach in most of the comparison scenarios. Moreover, the new mixed-bias combined approach performed at least as well as the other mixed-bias approaches in almost every case which showed that it is indeed a promising technique that may be further explored in order to increase performance further.

Our work can be extended in a number of ways. The first is to study the effect of different coefficients used in biasing parameters. The second area for future work is to experiment with the approaches presented in this paper in a test-bed environment. There are many examples of this type of research in literature [1,14]. It is often difficult to predict how a protocol or algorithm will perform with real hardware, even with the most sophisticated network simulation tools. At the same time, however, the simulation studies are effective way to obtain a starting point for work in the test-bed environments as they are flexible and allow changing simulation parameters easily during the experiments.

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