Enhancing Fairness in Wireless Multi-Hop Networks

(Invited Paper)

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ABSTRACT
Wireless multi-hop networks have recently been conceived as a networking paradigm. However, their deployment has been limited, mainly due to the fact that they lack fairness. In this research effort, we briefly review the state of art in fairness mechanisms in multi-hop networks and we propose an algorithm that tries to differentiate the traffic among the connections in a wireless multi-hop ad-hoc sensor network, so that the fairness is enhanced. This is achieved by an adaptive scheme, which tries to assign a higher priority to the traffic connections that experience delay greatly larger than the average, so that their delay is reduced, and the fairness of the system is improved.

Keywords
Multi-hop, fairness, interference, routing

1. INTRODUCTION
A wireless multi-hop network is a network that communication between two end nodes is carried out by hopping over multiple short wireless links. In such network, each node not only sends/receives packets to/from adjacent nodes, but also acts as a router and forwards packets for other nodes. Wireless multi-hop networks have many applications, including data monitoring, formation of community and indoor home networks and broadband access network to the Internet.

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Wireless multi-hop networks provide wide coverage, low cost deployment, as well as high data rates. However, despite these advantages, some weaknesses still appear in multi-hop networks. Fairness has been found to be limited in multi-hop networks. The topology of wireless multi-hop networks, in addition to the medium access control protocols that have been designed for single-hop networks, in relation to the spatial-temporal congestion variation are responsible for severe unfairness in these networks.

In this paper, we propose an algorithm that enhances the fairness by differentiating the traffic among the connections in a wireless multi-hop ad-hoc sensor network. This is achieved by an adaptive scheme, which tries to assign a higher priority to the traffic connections that experience delay greatly larger than the average, so that their delay is reduced, and the fairness of the system is improved.

The remainder of the paper is organized as follows: Section 2 overviews issues concerning fairness in wireless multi-hop networks. Section 3 presents several well-known fairness models and indices for wireless multi-hop networks. Section 4 presents several mechanisms that may be found into the literature to improve fairness in wireless multi-hop networks. Section 5 describes the propagation model and Section 6 presents the proposed algorithm and the simulation models, while Section 7 presents the simulation results. Finally, Section 8 concludes the paper.

2. FAIRNESS ISSUES IN WIRELESS MULTI-HOP NETWORK
Fairness is one of the key factors in order to evaluate the performance of a wireless network, since it ensures that well-behaved users will not penalized because of the excessive resource demands of aggressive users. Fairness can be largely divided into per-node and per-flow fairness. In per-node fairness,

equal access to the channel is given to the nodes irrespective of the number of flows traversing them while in per-flow fairness the access to the channel is in proportion to the number of flows that traverse them and act as relays [12].

Moreover, based on the length of the time that the network is observed, fairness can be defined on a short –term basis and on a long-term basis. A MAC layer can be considered as long-term fair if the probability of successful access to the channel observed on a long term converges to 1/N for N competing hosts. A MAC layer can be long-term fair, but short-term unfair [18].

In single-hop wireless networks, per node-fairness ensures that fairness will be a property of the entire network [17]. However, in multi-hop networks, since a user node has to transmit not only its own traffic but also the relayed traffic, fairness property cannot be ensured.

The first reason responsible for this unfairness is the network topology. The fact that the network is multi-hop, results in diverse distances among the sources and the destinations. Thus, some flows only require one transmission form source to destination, while other flows require multiple retransmissions. These added retransmissions result in increased delays. Thus some flows present vastly larger delay times than others, resulting in unfairness.

The second unfairness factor is related to the medium access control protocols. These protocols now used in multi-hop networks where initially designed for single-hop networks. They try to define the order of transmissions that will occur when a number of wireless stations compete for channel access. The result of this procedure is a time sharing sequence of transmission opportunities, with every competing wireless station having the same transmission probability. Thus, a packet that requires several retransmissions from source to destination will be involved in multiple channel access contentions, each of which may result in increased delays or even higher packet loss. Thus, the end-to-end delay times are significantly larger for flows that require more retransmissions, in contradiction to other ones that require fewer retransmissions, and yield smaller delay times. Moreover, the packet loss probabilities increase accordingly to the added retransmissions. Thus, it is evident that in order to enhance fairness in multi-hop networks, the medium access control protocols should be modified.

The third reason that generates unfairness in multi-hop networks is the spatial-temporal variation of the congestion levels in the network. As stated earlier, in single hop networks, all wireless stations compete to every other for access to the channel. As long as there is only one channel available, two simultaneous transmissions are not possible. Thus, every station's performance is influenced by the traffic that is generated by every other node in the network, meaning that a single congestion level is perceived throughout the network. On the contrary, simultaneous transmissions are possible in multi-hop networks. Thus, traffic generated in one part of the network, may not affect the congestion levels in distant areas. Therefore, some traffic flows will perceive the network to be highly congested, whereas at the same time, other traffic flows will perceive it to be non-congested. Thus the latter traffic flows will yield lower delay times, decreased packet loss and more available bandwidth that the former ones, resulting in added unfairness.

The fourth reason that may cause unfairness in multi-hop is the physical layer capture. Physical layer capture is the phenomenon where, in the event of a collision between two frames at a receiver, the hardware is capable of detecting and decoding the packet with a stronger strength [13]. If this effect happens consistently and frequently, it will cause severe unfairness since traffic from weaker signal senders will require more retransmissions.

3. FAIRNESS MODELS AND INDICES

Fairness models provide a formal idealized objective that can be used as a target and benchmark for protocol design and as a tool for studying alternatives for a network‘s fairness and performance objectives [9]. Two are the most commonly used fairness models: the Min-Max fairness model and the utility fairness model.

The notion of Min-max fairness [2], [6] - [8] was firstly adopted by the ATM forum to specify fairness in wireline data networks. Min-max fairness model splits the clients (nodes or the flows) into two non empty groups: the first group consists of the clients that cannot be completely satisfied by network resources and receive the same share of bandwidth; the second group consists of clients that need less bandwidth that their share and they receive exactly the amount of bandwidth that they ask for [16].

Utility fairness is based on a concative function U, called utility function that determines the fairness model for the system [3], [4].

$$H(x) = \sum_{j=1}^{n} U(x_j) \tag{1}$$

The most often used utility functions are

$$U(x,\xi) = \begin{cases} \dfrac{x^{1-\xi}}{(1-\xi)} & if \quad \xi \neq 1 \\ \log(x) & if \quad \xi = 1 \end{cases} \tag{2}$$

These utility functions incorporate the following objectives [15]:

- Rate maximization for $\xi = 0$
- Proportional fairness for $\xi = 1$
- Minimum potential delay $\xi = 2$
- Max-min fairness for $\xi \to \infty$

Also, in order to compute the effective fairness gain for the network several fairness indices have been proposed. These include

- Jain Fairness Index: Jain's fairness index [1] is the standard traditional measure of network fairness. If x_i, n, and $\overline{X}$ are the amount of allocated resource to the user (or to the flow) i, the total number of users, and the average allocated resource, respectively

$$F_J = \frac{\left(\sum_{i=1}^{N} x_i\right)^2}{N \cdot \sum_{i=1}^{N} x_i^2} \tag{3}$$

Absolute fairness is achieved when $F_J = 1$ and absolute unfairness is achieved when $F_J = 1/N$ [20].

- Gini Fairness Index: The Gini index is used in economics to quantify inequality of resource shares. It is derived from the Lorenz curve, which plots the cumulative share of aggregate throughput achieved by flows ranked from largest to smallest. The Gini index is capable of measuring the fairness at any instant of time during the execution of a scheduler.

$$F_G = \frac{1}{2n^2 x} \sum_i \sum_j \left| x_i - x_j \right| \quad (4)$$

The Gini fairness index varies between 0 and 1. Absolute fairness is achieved F_G=0. The higher value of F_G, near 1, indicates that there is higher unfairness among the proportion assignment of rates and fair share weight values.

4. FAIRNESS MECHANISMS IN WIRELESS MULTI-HOP NETWORKS

This section overviews mechanisms that may be used in order to alleviate fairness in wireless multi-hop networks.

4.1 Physical layer

Transmission power control will mitigate unfairness since it will counterbalance the signal strength of the senders and will reduce the physical layer capture [13].

4.2 MAC layer

Several mechanisms to enhance or to modify the MAC layer have been proposed. Ganu et al. [14] investigated the effect of physical layer capture in achieving per node throughput fairness wireless in IEEE 802.11 networks. More specifically, the authors conducted a test-bed and measure the effectiveness of several mechanisms to restore fairness, including transmission power control and back-off adjustments (MAC retry limit, Minimum contention window size, TXOP and AIFS adjustment) through the Wireless Multimedia Extensions derived from the IEEE 802.11e standards. Experimental results showed that combined TXOP and AIFS control yield an improvement of 25% in throughput fairness as compared to default settings.

A common approach to enhance fairness is fair queueing scheduling. These proposals invariably emulate fair queueing operations (i.e., assign start and finish tags for each packet) in a distributed manner by exploiting the broadcast nature of a wireless channel [19]. More specifically, Vaidya et al [4] presented a distributed fair scheduling algorithm for wireless LAN that emulates Self-Clocked Fair Queuing in a distributed manner and chooses a backoff interval that is proportional to the finish tag of the packet to be transmitted.

Nandagopal et al [5] proposed a mechanism that can translate any given fairness requirement into a matching contention resolution algorithm. Luo et al. [9] proposed a fair queueing scheme, the enhanced maximize-local-minimum fair queueing (EMLM), in which a flow is scheduled to transmit based on its rank in the sender as well as the rank in the receiver. Jun et al. [16] showed that per-flow queueing at the network layer can ensure fairness in wireless multi-hop networks at the expense of bandwidth efficiency. The authors also showed that per-flow queues at the network layer with MAC–layer QoS support may provide differentiated services in wireless multi-hop networks. He et al [19] proposed a new MAC protocol, the extended hybrid asynchronous time division multiple access (EHATDMA) to deal with the severe unfairness caused by the lack of synchronization problem, the double contention areas problem and the lack of coordination problem. Hsieh et al [12] proposed an ideal per-flow-fairness based MAC protocol that incorporates priorities to the nodes proportional to the number of flows that traverse each node.

4.3 Network layer

Barett et al. [12] studied the impact of the routing protocol in the determination of the overall fairness of the MAC layer. More specific, the authors conducted a detailed analysis of the short (and long) term fairness characteristics of two ad hoc network routing protocols, DSDV and DSR, together with the IEEE 802.11 MAC layer. Simulation results showed that fairness not only depends on the MAC protocol but also on the choice of routing protocol, and the various network parameters and traffic conditions. Also the DSDV protocol proved to provide better fairness in light loaded systems and less variability in terms of fairness from one run to the next for an experiment than DSR, except under high mobility.

Hsied et al [11] showed that load balancing at the routing layer will improve fairness. This is because of the fact that load balancing reduces the average degree of multiplexing of flows on a single link, and hence bounds the unfairness introduced by the MAC protocol. Another type of fairness for ad hoc networks is defined in [10]. Instead of considering a fair rate sharing, the authors consider a fair time sharing. They assume a physical model similar to 802.11. Two links can either transmit concurrently, or collide with each other forming a contention region. If several links compete for the same contention region, then time sharing is necessary and a form of maxmin fair time sharing is proposed. Although this approach alleviates the inefficiency of max-min fairness, it is difficult to generalize it to more general wireless physical models that include rate or power adaptations.

4.4 Transport layer

Xu et al. [11] showed that hidden and exposed terminal problems, large sensing and interfering ranges are the main reasons of unfairness among TCP flows over IEEE 802.11 MAC protocol.

5. PROPAGATION MODELING

A wireless channel is usually characterized by its broadcast nature, strong path loss, time varying fading and shadowing. Neglecting the delay of the propagation channel, the predicted received power of the sensor i can be estimated using the typical equation for radiowave path loss:

$$P_r(dB) = P_t(dB) + G_t(dBi) + G_r(dBi) - PL(dB) \quad (5)$$

where P_t the transmitted power of the sensor, G_t and G_r are the transmitted and received antenna gain (in dBi) and the path-loss (PL) component is given by

$$PL(dB) = 10n\log\left(\frac{4\pi d_{ab}}{\lambda}\right) \quad (6)$$

where d_{ab} is the distance between a transmit sensor node a and a receive sensor node b, n is the path-loss component, usually taking values between 2 and 4 for outdoor propagation and λ denotes the wavelength of the signal. Moreover, if the transmitted power of the sensor is not known and for simulation purpose is analytically given by:

$$P_t(dB) = E_b / N_o(dB) + R_b(dBHz) - 204(dBW / Hz) + FM(dB) \quad (7)$$

where the ratio E_b/N_o is the energy per bit that depends on the physical channel, the modulation scheme used, and the targeted bit-error-rate (BER), R_b is the transmitted bit rate in bit/sec $R_b=1/T_b$, the value -204 stands for the thermal noise power spectral density N_o for a typical temperature of T=27^{o}C, and FM is the safety margin called Fading Margin always used in mobile communications, with a typical value of 10 dB.

Taking into consideration the shadowing due to large-scale fading effects of the channel, the path-loss component can be expressed by:

$$PL(dB) = 10n\log\left(\frac{4\pi d_{ab}}{\lambda}\right) + X_\sigma \quad (8)$$

where X_σ is the log-normal distribution variable with zero mean and the user-defined standard deviation σ_x states the large-scale fading effects of the channel [22].

Additionally, taking into account the small-scale fading of the channel due to scattering effects of the components surrounded the sensors, the propagation is given according to the probability density function (pdf) used for deriving the random effect of multipath delay components of the signal. The most widely used distribution functions describing the statistical time varying nature of the received envelope of the multipath components are the Rayleigh pdf (for NLOS) and Rician pdf (for LOS) [23].

In multi-hop networks, an additional problem is raised; the additive interference of the sensor nodes enclosed in the transmission area between two active nodes. A wireless signal is decoded by treating the sum of all the other signal transmissions and environmental disturbances, as noise. As already described, the decoding is probabilistic, and the success or failure of a signal transmission can be expressed in terms of a bit/packet error probability which depends on the Signal-to-Interference-and-Noise-Ratio (SINR). If two transmitters transmit on the same frequency band, a receiver of one can receive power from the second having fading and shadowing in addition to signal attenuation (path loss). Thus, SINR is given by the following expression for transmission from i to j sensor node:

$$SINR_{ij} = \frac{\left(\frac{d_{ij}}{d_o}\right)^{-n} F_{ij}P_i}{N_o + \sum_k \left(\frac{d_{kj}}{d_o}\right)^{-n} F_{kj}P_k} \quad (9)$$

where d_{ab} is the distance between two nodes a and b, k is the number of interference nodes, d_o is the near-field distance of the transmitter, F_{ab} is the fading variables (attenuation) between nodes a and b (such as rayleigh and rician) and P is the received power. A packet reception at a defined data-rate is successful, provided that throughout the duration of the packet transmission SINR is always greater than a threshold corresponding to an acceptable BER, depending on the modulation scheme. If at any point during the packet transmission the threshold effect does not hold, then there is a collision.

6. SINR BASED DIFFERENTIATION AND SIMULATION SCENARIO

The key idea of the paper is an algorithm that enhances the fairness by differentiating the traffic among the connections in a wireless multi-hop ad-hoc sensor network. This is achieved by an adaptive scheme, which tries to assign a higher priority to the traffic connections that experience delay greatly larger than the average, so that their delay is reduced, and the fairness of the system is improved.

The admission control policy takes into consideration the active flows that have previously been admitted in the network. A new flow cannot be admitted if the SNIR for every transmission it consists of falls below a threshold, or if the new transmissions cause the SNIR of a previously established connection to fall below the threshold. The differentiation if realized by assigning a different threshold to the SINR according to the priority.

Specifically, the network configuration contains two SINR thresholds, SINR_Hi and SINR_Low, which are both considered to be higher than the physical layer limitations. All connections by default use the SINR_Hi. However, if the resulting delay of an attempted connection exceeds a transitional value, then the flow is reestablished using the SINR_Low value. The two delays that are produced by the two different connection approaches are compared to the average delay of the system, and route that produces a delay closer to the average is used.

The network model consists of a single channel ad-hoc sensor network. The topology of the network consists of 25 nodes that are located on a square grid, with a side of 5 nodes. The distance among two consecutive nodes is 10m. The physical layer is modeled as an ideal receiver that may decode without errors any signal that is received, as long as the SINR exceeds a threshold. Otherwise, the signal cannot be decoded and the transmission is lost. The wireless channel is modeled as a non-fading channel, with a path loss that is proportional to the 4th power of the distance. All nodes transmit at the same power level. The channel characteristics are summarized in Table 1.

The MAC layer that is used is TDMA with dynamic end-to-end Scheduling [21]. The routing protocol discovers the route that follows the shortest path, with respect to the end-to-end delay, taking into consideration the current state of the system. The TDMA frames have a size of 10 slots. The traffic generator selects the source and the destination of every connection randomly, using a uniform distribution. The duration of each connection depend on the desired congestion level of the network.

Table 1. Channel simulation's characteristics

Attribute	Value
Near Field distance d_0	1.0
N	4
Signal power at d_0	30000
Background Noise N	1
SINR_Hi	20
SINR_Low	10

7. SIMULATION RESULTS

In this section we present the merit of the proposed fairness enhancement methodology, by comparing it to the conventional approach, where a single threshold is used. Therefore, we consider threes cases: In the 1st case, all connections are established the SINR_Low threshold of 10, in the 2nd case the SINR_Hi threshold is equal to 20. Finally, in the 3rd case we examine the proposed fairness scheme. Initially, we tested the architecture on different congestion levels, and the results are depicted on Figure 1. Following, we generated some more results for the 5 concurrent active connections. In order to obtain confidence intervals on the results, we executed each simulation 10 times, depicted in Table 2.

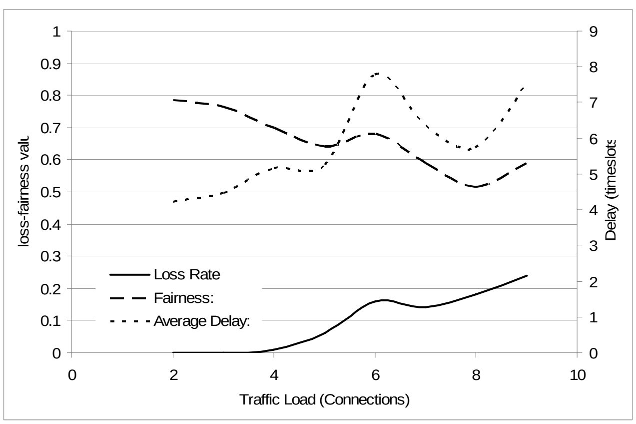

Figure 1. Loss Rate, Average delay, and fairness for varying congestion levels.

Table 2. Simulation results for Case 1

Loss Rate	Average Delay	Fairness
0.06	5.37234	0.599565
0.05	7.252632	0.569336
0.09	6.340659	0.669208
0.06	5.893617	0.604641
0.07	6.397849	0.683065
0.03	5.340206	0.679329
0.1	6.477778	0.629949
0.06	5.755319	0.689008
0.07	6.849462	0.669907
0.06	6.680851	0.540249

Case 2 was produced using the threshold value of 20. We observed a higher loss rate, equivalent delay, and equivalent fairness, as depicted in Table 3, while in Case 3 the described adaptive scheme was used and the results are depicted at Table 4.

The average measures and their confidence intervals appear on Figure 2. In should be mentioned that the fairness of the algorithms are evaluated using Jain's Fairness Index (Equation 3). As, it can be seen from the obtained results, the proposed scheme achieved better fairness than the other schemes, and reduced delay. However, the loss rate is not the smallest possible. The measured results are statistically significant for the given topology.

Table 3. Simulation results for Case 2

Loss Rate	Average Delay	Fairness
0.21	5.481013	0.550772
0.27	6.712329	0.655449
0.22	5.961538	0.667176
0.23	6.350649	0.647377
0.29	6.225352	0.522721
0.19	5.765432	0.573229
0.22	6.141026	0.666263
0.27	6.479452	0.594526
0.26	5.216216	0.548926
0.28	6.166667	0.679742

Table 4. Simulation results for Case 3

Loss Rate	Average Delay	Fairness
0.3	4.871429	0.793673
0.16	3.547619	0.755136
0.25	5.106667	0.758965
0.24	5.092105	0.732309
0.21	5.025316	0.804132
0.22	4.615385	0.74375
0.26	4.364865	0.733915
0.21	4.050633	0.752731
0.24	4.381579	0.716282
0.25	5.093333	0.725449

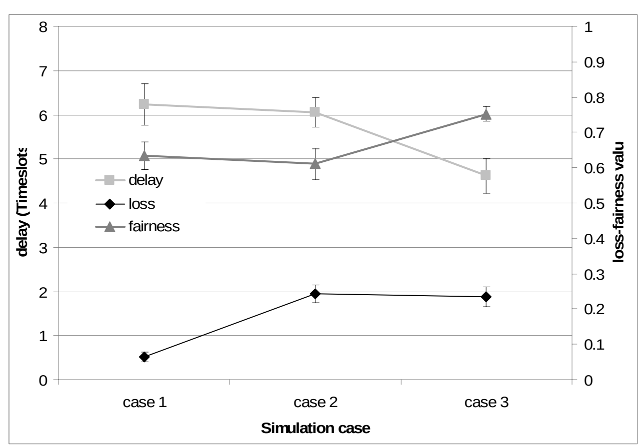

Figure 2. The average loss, delay and fairness, along with their 0.02 confidence intervals, for the three cases.

8. CONCLUSIONS

A wireless multi-hop network is a network that communication between two end nodes is carried out by hopping over multiple short wireless links. Wireless multi-hop networks provide wide coverage, easy and low cost deployment, as well as high data rates. However, despite these advantages, fairness has been found to be limited in multi-hop networks. The topology of wireless multi-hop networks, in addition to the medium access control protocols that have been designed for single-hop networks, in relation to the spatial-temporal congestion variation are responsible for severe unfairness in these networks.

In this paper, we propose an algorithm that enhances the fairness by differentiating the traffic among the connections in a wireless multi-hop ad-hoc sensor network. This is achieved by an adaptive scheme, which tries to assign a higher priority to the traffic connections that experience delay significantly larger than the average, through various limitations. The simulation results showed that the fairness of the system is improved, as well as their delay is reduced proposed fairness scheme.

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