ReDEx: Receiver Diversity Exploitation Mechanism for 802.11 Wireless Networks

Bachar Wehbi, Anis Laouiti and Ana Cavalli
Institut TELECOM, TELECOM & Management SudParis, CNRS SAMOVAR
9 rue Charles Fourier, 91011 Evry Cedex, France
{bachar.wehbi, anis.laouiti, ana.cavalli}@it-sudparis.eu

***Abstract*— Our objective is to increase the individual throughput of each node in the network by exploiting neighbors with more favorable channel conditions in terms of bit rate and packet loss ratio. We propose a per-neighbor message queue in order to reduce the effect of the Head Of Line (HOL) blocking problem of IEEE 802.11. A weighted queuing scheduler grants each neighbor a service proportional to its channel conditions. The sender maintains a separate backoff counter for each neighbor and adopts a dynamic binding strategy to avoid multiple transmissions to a neighbor with bad channel conditions. We use a continuous time Markov chain model to study the proposed mechanism and to derive the correspondent parameters optimizing the channel utilization. The Matlab simulations show good expected performance gain compared to the standard implementation of IEEE 802.11.**

***Index Terms*— Wireless network, Scheduling, Markov chain modeling, Receiver diversity, Optimization**

I. INTRODUCTION

We consider the IEEE 802.11 standard [1]; while many protocols have been proposed to improve the bandwidth exploitation between multiple senders [5], [6], the works on improving the individual throughput of a node transmitting to multiple neighbors remains limited [8]. Receiver diversity exploitation falls in the latter category. In order to improve its throughput, a node can grant each of its neighbors a service proportional to the channel conditions (i.e. like packet loss and bit rate) with that neighbor.

Traditionally, the IEEE 802.11 functions are implemented in driver firmware. The driver implements a FIFO interface queue where packets destined to the different destinations are queued. Once the interface is ready, the sender dequeues a packet, waits until the channel is clear before trying to transmit the packet. In the case of a transmission failure, the sender retries until it succeeds or the maximum retry limit is exceeded (the packet is dropped then). Accordingly, if the link conditions to the intended neighbor are bad, the packet will encounter additional delay due to the time spent in exponentially backing off retrying transmitting to a bad neighbor. Another problem arises of the usage of a single interface queue. The 802.11 standard allows for multi bit rate; a station transmits on higher bit rates when the channel is favorable. When the sender maintains a single message queue, packets waiting for transmission to neighbors with favorable channel conditions will experience higher delays waiting the transmissions on lower bit rates to neighbors with bad channel conditions. The 802.11 standard suffers from this Head Of Line (HOL) blocking problem that prevents increasing the individual throughput by exploiting the receiver diversities. For example, consider the network illustrated in figure 1 composed of a sender A and two neighbors, B with good channel conditions (higher bit rate, lower packet loss ratio) and C with bad channel conditions (lower bit rate, higher packet loss ratio). Hence, a packet destined to node B will encounter a longer delay waiting the transmission to C. This HOL problem reduces the individual throughput of node A. The implementations of the standard 802.11 are not designed with any option to exploit this kind of receiver diversity.

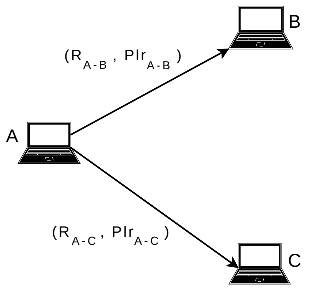

Fig. 1. Simple network scenario.

In this paper we propose $ReDEx$, a receiver diversity exploitation mechanism that tries to improve the individual throughput of nodes by reducing the HOL blocking problem and by prioritizing neighbors with more favorable channel conditions. The rest of the paper is organized as follows: In section II-A we describe the $ReDEx$ mechanism; we model it using continuous time Markov chain is section II-C. In section III we evaluate $ReDEx$ using Matlab simulations and compare it to the standard 802.11. We conclude in section IV

II. RECEIVER DIVERSITY EXPLOITATION (REDEX) IN 802.11 WIRELESS NETWORKS

Receiver Diversity Exploitation (ReDEx) tries to improve the individual throughput of a node transmitting to multiple neighbors. $ReDEx$ reduces the HOL blocking problem and prioritizes transmissions to neighbors with more favorable channel conditions. With $ReDEx$, a sender node grants active neighbor[1] a service proportional to the channel conditions (i.e. like packet loss and bit rate) in order to prioritize transmissions to more favorable active neighbors.

A. ReDEx Description and Functionalities

$ReDEx$ proposes a modification to the transmitter side of IEEE 802.11 to exploit the previously mentioned receiver diversities. When a node is transmitting to multiple destinations, the active neighbors with more favorable channel conditions should be prioritized over those with less favorable conditions. For this end, each node maintains a separate message queue for every active neighbor. A weighted fair scheduler grants each message queue a service proportional to the neighbor's channel conditions. The scheduler calculates the weights corresponding to each active neighbor from its transmission bit rate and packet loss ratio in such a way to satisfy the throughput fairness trade off[2]. Moreover, the sender maintains a separate backoff counter for each neighbor. $ReDEx$ adopts a dynamic binding strategy where a packet is unbound from the wireless interface following a transmission failure. The scheduler selects a packet from one of the message queues with a probability equivalent to the corresponding active neighbor's weight. It binds the selected packet to the wireless interface and waits it gets access to the channel before transmitting the packet. If the transmission fails, and the maximum retry limit is not exceeded, the device driver unbinds the packet and queues it back on top of the corresponding message queue. Then it re-schedules a packet for transmission which may be or not be the same, binds it to the channel and tries to transmit it. This dynamic binding strategy permits to exploit channels with more favorable conditions while reducing the effect of the HOL blocking problem of the static binding strategy of 802.11.

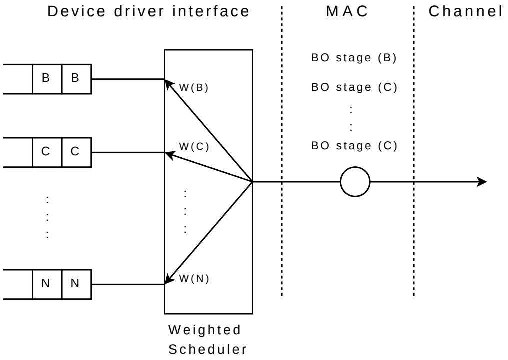

Fig. 2. The sender side model of ReDEx.

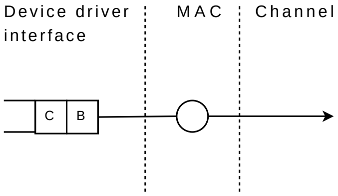

Fig. 3. The sender side model of the standard 802.11 MAC.

The sender side model of $ReDEx$ and that of 802.11 are illustrated in figures 2 and 3 respectively. In figure 2 separate message queues are maintained for the different active neighbors of the node. To each message queue corresponds a service weight affected by the scheduler to indicate its priority (service share). On the MAC level, per-receiver backoff counters are maintained to track the channel conditions to the corresponding active neighbor.

In order to better understand $ReDEx$ let's take the simple example illustrated in figure 1 where sender node A has concurrent transmissions to node B on $11Mbps$ and to node C on $2Mbps$. A maintains two message queues for its two active neighbors. Assume for instance that the weights corresponding to each of the message queues are proportional to the transmission bit rate; that is $W_B = 5.5 * W_C$. Therefore, $ReDEx$'s scheduler selects with higher priority a message from B's message queue. Imagine now that a transmission to C fails. Instead of trying immediately to retransmit the message, $ReDEx$ adopts a dynamic binding strategy. The failed message is queued back on top of C's message queue, and then the scheduler selects a message to transmit. This message may be the same with a probability proportional to C's weight. It has been shown [3] that the losses in wireless networks are bursty; the dynamic binding strategy of $ReDEx$ allows therefore the exploit the receiver diversity by avoiding multiple transmission to the same bad receiver.

The objective of $ReDEx$ is first to reduce the effect of HOL while at the same time optimizing the individual throughput of each node. Recall that with perfect channel conditions (no packet loss) a transmission on $2Mbps$ will take approximately 5.5 times more than a transmission at $11Mbps$. $ReDEx$ grants each message queue a share of the bandwidth proportional to the link conditions to the corresponding neighbor.

B. Properties of $ReDEx$

$ReDEx$ distributes the individual available channel time between the different active neighbors of a sender. The objective is to mitigate the HOL blocking problem in the one hand and exploiting the receiver diversity of the wireless channel to better distribute the available channel time between the different active neighbors in the other hand. These properties are satisfied thanks to the dynamic binding strategy and the weighted fair scheduler that grants each per-receiver message queue a service proportional to the channel conditions to that receiver. In the following we will discuss these mentioned properties of $ReDEx$.

1) Per-Active Neighbor Service Allocation: We consider here the service allocation between the different message queues (active neighbors) of the sender node according to the scheduling strategy. $ReDEx$ scheduler distributes the service

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[1] $ReDEx$ considers the direct neighbors of a sender node. These neighbors may be the final destination of the data transmission or relay nodes on the path from the sender to the final destination. For simplicity of presentation, we will denote by *active neighbors* the set of neighbors that a given sender is transmitting to.

[2] Maximizing the throughput can be achieved by avoiding transmissions to unfavorable neighbors. This strategy however is unfair and leads to starvation problems.

between the different queues according to the weights given for each message queue. Assume the sender is transmitting to N different neighbors $\{N_1, N_2, \cdots, N_N\}$ with bit rates ρ_i and packet loss ratio p_i. The sender maintains a separate message queue for each of these receivers. The weighted fair scheduler grants a weight w_i to each of the message queues. The service allocation distribution between the different queues is therefore equivalent to their weights. Two particular properties should be satisfied:

- the weights should be proportional to the transmission bit rates to the corresponding receivers. If transmission to node I is faster than transmission to node J, then the weights corresponding to I's message queue should be higher than that of node J. In other words, for the same packet loss probability, the message queue weights should respect $\frac{w_i}{w_j} \simeq \frac{\rho_i}{\rho_j}$.
- The weights should be proportional to the transmission success rate to the correspondent receivers. If the packet loss to node J increases then the weight of node J should decrease. Similarly, if the packet loss to node I increases, its corresponding service weight should decrease. In other words, for the same transmission bit rate, the message queue weights should respect $\frac{w_i}{w_j} \simeq \frac{(1-p_i)}{(1-p_j)}$.

Accordingly, if we consider the transmission bit rate and the packet loss ratio, $ReDEx$ grants each active neighbor N_i a service weight W_i where:

$$\forall N_i, N_j \in \{N_1, N_2, \cdots, N_N\}, \quad \frac{W_i}{W_j} = \frac{\rho_i \cdot (1-p_i)}{\rho_j \cdot (1-p_j)}$$

The normalization of the previous equation gives:

$$W_i = \frac{\rho_i \cdot (1-p_i)}{\sum_{j=1}^{j=N} [\rho_j \cdot (1-p_j)]}$$

2) High Individual Throughput: The global throughput of the network is the sum of the individual throughputs of each node in the network. Therefore, improving the individual throughputs of the nodes implies an increment of the global throughput. When a sender node has multiple transmissions to different neighbors on different bit rates, maximizing its individual throughput is equivalent to transmitting only to the neighbors with the highest bit rates. This will engender a starvation problem to the transmissions on lower bit rates. In order to satisfy the fairness-throughput trade off, we grant each transmission a service weight corresponding to the channel conditions. On the other hand, the HOL blocking problem will decrease the available throughput of a node due to the repeated retransmissions when the channel conditions to the receiver are bad.

Using $ReDEx$, the dynamic binding strategy mitigates the HOL blocking problem by trying to transmit to other neighbors when the channel conditions to a particular neighbor are unfavorable. In addition, the per-neighbor message queue and the weighted fair scheduler allows $ReDEx$ to grant each active neighbor a service proportional to its channel conditions.

C. Modeling and Analyzing ReDEx

In order to analyze $ReDEx$, we model the MAC protocol operations of the simple network illustrated in figure 1 where sender A transmits simultaneously to its active neighbors B and C. The links from A to B and to C have different bit rates and packet loss ratios. We consider the saturation condition where A has always a packet for transmission in each message queue. According to $ReDEx$, A maintains two backoff counters, one for B and one for C. When a transmission fails, the contention window for the failed receiver is adjusted according to the exponential backoff strategy of 802.11. Then, $A's$ wireless device unbinds the packet from the channel and reschedules a packet - which may be the same - for transmission. Now if the transmission succeeds, the device resets the corresponding backoff counter and re-schedules a new packet for transmission.

We model the sender side MAC protocol operations using continuous time Markov chain. Let $P_B(t)$ and $P_C(t)$ be the stochastic processes representing the state of the transmission to nodes B and C at time t. Each process can be in the sending state s or in a backoff stage i where $i \in [0, m]$ with m the maximum backoff stage. As we are considering an example with two receivers, we can model the bi-dimensional process $\{P_B(t), P_C(t)\}$ using the continuous time Markov chain illustrated in figure 4. Denote T_i the time spent at stage i, $T_{BO}(i)$ the backoff time spent at stage i and T_s the time spent by the station transmitting a packet. The time T_i is function of $T_{BO}(i)$ which is uniformly distributed on $[0, (2^i CW_{min} - 1)\delta]$ where δ is the slot time duration and T_s depends on the packet length and the transmission bit rate. In order to employ a continuous time Markov chain model for the analysis we make the approximation that T_i and T_s are exponentially distributed with mean $E[T_i]$ and $E[T_s]$ given by:

$$E[T_i] = \mu_i = T_{DIFS} + T_{RTS} + T_{CTS} + 2T_{SIFS} + T_{BO}(i)$$

$$E[T_s] = \mu_s = T_{DATA} + T_{ACK} + T_{DIFS} + T_{SIFS}$$

We should note here that we assume there are no other concurrent transmissions in the network. This assumption allows us to study the per receiver share of the bandwidth available for a given sender node. In this Markov model the state transition rates are the following:

$$\begin{array}{l}
q(s,j) \rightarrow q(0,j) = 1/\mu_s(B) \quad with\ (j \in T - \{s\}) \\
q(i,s) \rightarrow q(i,0) = 1/\mu_s(C) \quad with\ (i \in T - \{s\}) \\
q(i,j) \rightarrow q(s,j) = w_B \cdot (1-p_B)/\mu_i(B) \\
\qquad\qquad with\ (i,j \in T - \{s\}) \\
q(i,j) \rightarrow q(i,s) = w_C \cdot (1-p_C)/\mu_i(C) \\
\qquad\qquad with\ (i,j \in T - \{s\}) \\
q(i,j) \rightarrow q(i+1,j) = w_B \cdot p_B/\mu_i(B) \\
\qquad\qquad with\ (i \in T - \{s,m\}, j \in T - \{s\}) \\
q(i,j) \rightarrow q(i,j+1) = w_C \cdot p_C/\mu_i(C) \\
\qquad\qquad with\ (i \in T - \{s\}, j \in T - \{s,m\}) \\
q(m,j) \rightarrow q(0,j) = w_B \cdot p_B/\mu_m(B) \quad with\ (j \in T - \{s\}) \\
q(i,m) \rightarrow q(i,0) = w_C \cdot p_C/\mu_m(C) \quad with\ (i \in T - \{s\})
\end{array} \tag{1}$$

The first two equations account for the rate at which the transmitting station finishes the sending state; this time depends only on the transmission bit rate (as we consider packets of the same length). The third equation accounts

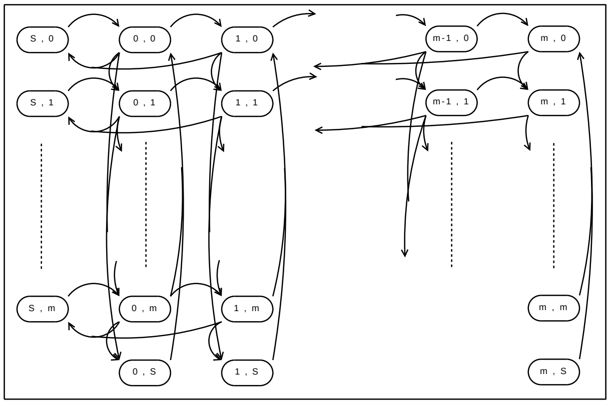


Fig. 4. Markov chain model of the sender side interactions of $ReDEx$.

for the rate at which a transmission destined for receiver B succeeds when the correspondent backoff is at stage i. Where the forth equation is the rate at which the transmission for receiver C succeeds when the correspondent backoff is at stage j. The fifth to the eighth equations correspond to the rate of transmission failure to destinations B and C. The last two equations represent also the rate of packet drop. In these equations w_B and w_C represent the scheduler weights of the message queues for receivers B and C where p_B and p_C represent their packet loss ratios.

Now let $\pi(i,j) = lim_{t\to\infty} P\{P_B(t) = i, P_C(t) = j\}$ $i, j \in T$ be the invariant probabilities of the Markov chain. Since we have specified all the transitions in the Markov chain, we can compute the invariant probabilities by numerical methods and hence, various performance metrics can be estimated. In order to compute the numerical results, we use the parameters from the IEEE 802.11 standard. We assume the packets are of the same length and the error loss probabilities p_B and p_C are uniformly distributed. The service weights w_B and w_C are function of the transmission bit rate and the packet loss ratio, the only two parameters influencing our model. They are chosen to satisfy the *throughput-fairness* trade off; they are given by $w_B = \frac{(1-p_B)/\mu_s(B)}{[(1-p_B)/\mu_s(B)+(1-p_C)/\mu_s(C)]}$ and $w_C = 1 - w_B$, where $\mu_s(B)$ and $\mu_s(C)$ are the times spent to transmit a packet of a given fixed length to nodes B and C respectively. We note here that this is a simple model with some simplifying assumptions consisting of one sender transmitting to two different receivers. It serves our purpose of proving the effectiveness of exploiting the receiver diversity in wireless networks. Applying the property of continuous time Markov chains given in equation 2,

$$\sum_{i\neq j} \pi_i \mu ij = \sum_{i\neq j} \pi_j \mu ji \tag{2}$$

We get that:

$$\pi(s,j)/\mu_s(B) = \sum_{i\in T-\{s\}} w_B(1-p_B)\pi(i,j)/\mu_i(B)$$

and

$$\pi(S_B)/\mu_s(B) = \pi(s,\cdot)/\mu_s(B) = \sum_{j\in T-\{s\}} \pi(s,j)/\mu_s(B)$$

$$= \sum_{j\in T-\{s\}} \sum_{i\in T-\{s\}} w_B(1-p_B)\pi(i,j)/\mu_i(B) \tag{3}$$

Similarly

$$\pi(S_C)/\mu_s(C) = \pi(\cdot,s)/\mu_s(C) = \sum_{i\in T-\{s\}} \pi(i,s)/\mu_s(C)$$

$$= \sum_{i\in T-\{s\}} \sum_{j\in T-\{s\}} w_C(1-p_C)\pi(i,j)/\mu_i(C) \tag{4}$$

Using equations 3 and 4 we can deduce the fraction of time spent sending for B over that spent sending for C given in equation 5:

$$\frac{\pi(S_B)}{\pi(S_C)} = \frac{\mu_s(B)\cdot w_B\cdot(1-p_B)}{\mu_s(C)\cdot w_C\cdot(1-p_C)} \tag{5}$$

In order to compare $ReDEx$ with the standard 802.11 we use the same methodology to model the sender side interactions of the standard MAC using continuous time Markov chain. Several works tried to model in detail the 802.11 MAC in the literature [2], [4]. More recently, the authors in [7] revisited the CSMA/CA in 802.11 MAC and proposed a more effective model as they claim. Our model is different as it tries to capture the interactions seen by a node transmitting to several destinations and not the distribution of the channel time between multiple concurrent senders as in the mentioned references. The objective of the model is to analyze and derive the per-neighbor shares of the channel time available at a single node. Again, for sake of simplicity, we model the simple network of a sender A transmitting to receivers B and C. The Markov chain model illustrated in figure 5 has the following state transition rates:

$$\begin{array}{l}
q(S(i)) \to q(0(j)) = 1/2\cdot 1/\mu_s(i) \quad with\ (i,j\in\{B,C\}) \\
q(i(B)) \to q(S(B)) = (1-p_B)/\mu_i(B) \quad with\ (i\in T-\{s\}) \\
q(i(C)) \to q(S(C)) = (1-p_C)/\mu_i(C) \quad with\ (i\in T-\{s\}) \\
q(i(B)) \to q(i+1(B)) = p_B/\mu_i(B) \quad with\ (i\in T-\{s,m\}) \\
q(i(C)) \to q(i+1(C)) = p_C/\mu_i(C) \quad with\ (i\in T-\{s,m\}) \\
q(m(i)) \to q(0(j)) = 1/2\cdot p_i/\mu_m(i) \quad with\ (i,j\in\{B,C\})
\end{array} \tag{6}$$

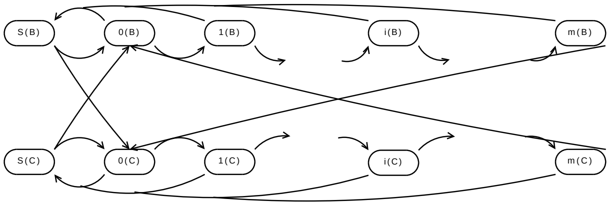


Fig. 5. Markov chain model of the sender side MAC interactions of the IEEE 802.11 standard.

The first equation accounts for the rate at which the transmission station finishes sending to one of the neighbors B or C. The station will be then ready for a new packet which could be destined, with equal probability, to either destination (where the 1/2 in the equation). The second and third equations account for the rate at which a transmission at backoff stage i succeeds. Where the rest of the equations account for the rates at which transmission on backoff stage i fails; in addition the last equation corresponds to the packet drop rate where at the m^{th} backoff stage a packet failure is translated into packet drop. Applying the property of continuous time Markov chains given in equation 2 we get equation 7 given below:

$$\frac{\pi_{S(B)}}{\mu_s(B)} = (1-p_B)\cdot\frac{\pi_{0(B)}}{\mu_0(B)} + \cdots + (1-p_B)\cdot\frac{\pi_{m(B)}}{\mu_m(B)} \quad (7)$$

Applying the same property we deduce the relation between $\pi_{i(B)}$ and $\pi_{0(B)}$ given in equations:

$$(1-p_B)\cdot\frac{\pi_{1(B)}}{\mu_1(B)} + p_B\cdot\frac{\pi_{1(B)}}{\mu_1(B)} = p_B\cdot\frac{\pi_{0(B)}}{\mu_0(B)}$$

$$\Rightarrow\ \pi_{1(B)} = p_B\cdot\frac{\mu_1(B)}{\mu_0(B)}\cdot\pi_{0(B)} \quad (8)$$

Similarly we get that:

$$\pi_{i(B)} = p_B\cdot\frac{\mu_i(B)}{\mu_{i-1}(B)}\cdot\pi_{i-1(B)} \quad (9)$$

Using equations 8 and 9 we get:

$$\pi_{i(B)} = p_B^i\cdot\frac{\mu_i(B)}{\mu_0(B)}\cdot\pi_{0(B)} \quad (10)$$

Replacing equation 10 in equation 7 we get $\pi_{S(B)}$ in function of $\pi_{0(B)}$ given in equation 11:

$$\frac{\pi_{S(B)}}{\mu_s(B)} = \frac{(1-p_B)}{\mu_0(B)}\cdot\pi_{0(B)}\cdot\sum_{i=0}^{m} p_B^i = (1-p_B^{m+1})\cdot\frac{\pi_{0(B)}}{\mu_0(B)} \quad (11)$$

Similarly we have:

$$\frac{\pi_{S(C)}}{\mu_s(C)} = \frac{(1-p_C)}{\mu_0(C)}\cdot\pi_{0(C)}\cdot\sum_{i=0}^{m} p_C^i = (1-p_C^{m+1})\cdot\frac{\pi_{0(C)}}{\mu_0(C)} \quad (12)$$

On the other hand we can get the following relation between $\pi_{0(B)}$ and $\pi_{0(C)}$:

$$\frac{\pi_{0(B)}}{\mu_0(B)} = \frac{\pi_{0(C)}}{\mu_0(C)} = \frac{\pi_{S(B)}}{2\cdot\mu_s(B)} + \frac{p_B\cdot\pi_{m(B)}}{2\cdot\mu_m(B)} + \frac{\pi_{S(B)}}{2\cdot\mu_s(B)} + \frac{p_C\cdot\pi_{m(C)}}{2\cdot\mu_m(C)} \quad (13)$$

Using the property given by equation 13 in equations 11 and 12 we get the relation between the fractions of time spent transmitting to node B and node C given by equation 14 below:

$$\frac{\pi_{S(B)}}{\pi_{S(C)}} = \frac{(1-p_B^{m+1})\cdot\mu_s(B)}{(1-p_C^{m+1})\cdot\mu_s(C)} \quad (14)$$

Equations 5 ($ReDEx$) and 14 (802.11) giving the fractions of time spent transmitting to the different receivers show the improvement we can get by using $ReDEx$. On the first hand, equation 14 shows that the channel time distribution using 802.11 is less sensitive to the packet loss (p^{m+1}). This is due to the HOL blocking problem of 802.11 where the sender keeps trying to transmit a packet until it succeeds or the packet is dropped (multiple failures). On the other hand, the channel time distribution of 802.11 is proportional to the time required to transmit a packet. This means that 802.11 is reversely proportional to the transmission rate. $ReDEx$ succeeds to mitigate 802.11 problems. Equation 5 shows that the channel time distribution using $ReDEx$ is proportional to the packet success ratio $(1-p)$, this is the impact of the dynamic binding strategy that reduces considerably the HOL blocking problem. In addition, $ReDEx$ channel time distribution is proportional to the active neighbors' weights w_i allowing therefore to exploit the multi-rate feature of 802.11 and improve the individual throughput of a node.

D. *Generalizing ReDEx: Transmissions to N neighbors*

The evaluation of $ReDEx$ based on a simple model of one sender and two receivers can be generalized. The dynamic binding property of $ReDEx$ makes the transition from any backoff stage to the sending state to a given active neighbor proportional the that neighbor's weight. This is shown in equations 3 and 4 of the two dimensional $ReDEx$ model that led to equation 5 giving the ratio of the send time to the two different neighbors. If we assume now the general scenario of a sender transmitting to the set $\{N_1, N_2, \cdots, N_N\}$ of active neighbors, the ratio of the send time to any two given active neighbors can be formulated in equation 15:

$$\forall N_i, N_j,\quad \frac{\pi(S_{N_i})}{\pi(S_{N_j})} = \frac{\mu_s(N_i)\cdot w_{N_i}\cdot(1-p_{N_i})}{\mu_s(N_j)\cdot w_{N_j}\cdot(1-p_{N_j})} \quad (15)$$

This equation can be normalized yielding to the distribution of the send time between the different active neighbors of a sender node. The fraction of the send time $\pi(S_{N_i})$ to active neighbor N_i is therefore:

$$\forall N_i,\quad \pi(S_{N_i}) = \frac{\mu_s(N_i)\cdot w_{N_i}\cdot(1-p_{N_i})}{\sum_{j=1}^{J=N}\mu_s(N_j)\cdot w_{N_j}\cdot(1-p_{N_j})} \quad (16)$$

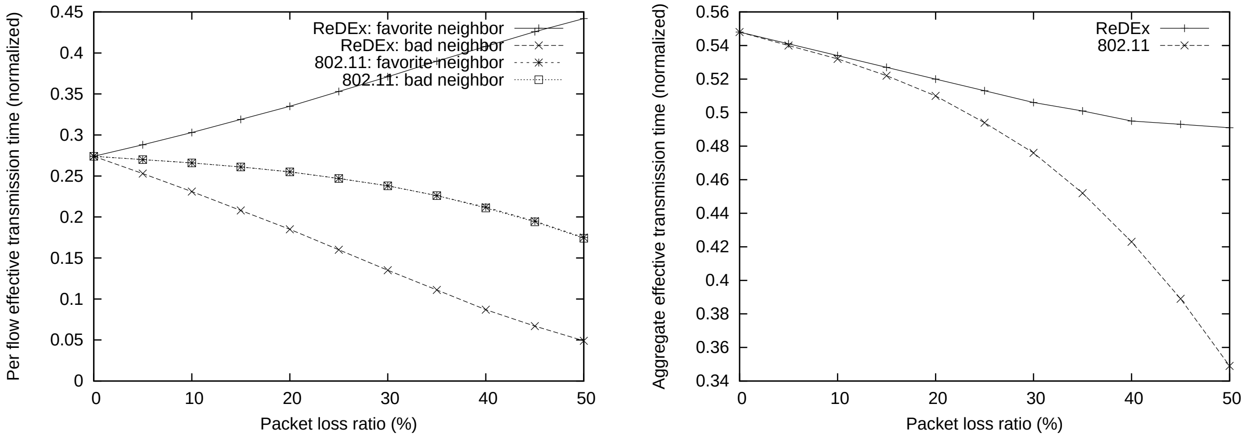
III. EVALUATION AND DISCUSSION

In order to evaluate $ReDEx$, we used Matlab simulations to derive its expected performance compared to the standard 802.11. We implemented the continuous time Markov chain models illustrated in figures 4 and 5. The analysis of these models provides the invariant probabilities which are the time fractions the system spend in each of the model's states. Using these invariant probabilities, we can deduce interesting performance parameters.

A. *Effect of Packet Loss*

In this section the effect of packet loss on $ReDEx$ and 802.11 is studied. We consider the scenario of one node A sending to its two neighbors B and C. In order to isolate the packet loss effect, we assume both links have the same transmission bit rate (11Mbps), one of the links has perfect channel conditions (no packet loss) where the second suffers from a packet loss p uniformly distributed.

In figure 6-a, we can see that 802.11 provides equal shares of the transmission time between the different neighbors; therefore, when a neighbor experiences high packet loss, the transmission times to the rest of the neighbors drop though the channel conditions have not changed. However, $ReDEx$ adapts to the channel conditions; when a neighbor experiences high packet loss, the scheduler grants its corresponding message queue less access priority while, at the same time, increasing the access priority of the neighbors with more



(a) (b)

Fig. 6. Aggregate and per neighbor transmission time in function of the packet loss ratio with a fixed bit rate of our mechanism and the standard 802.11.

favorable conditions. Hence, the transmission time to the neighbor with favorable conditions is increased.

Figure 6-b illustrates the variation of the aggregate effective transmission time $\pi(S) = \pi_s(B) + \pi_s(C)$, when using $ReDEx$ and the standard implementation of 802.11. Using the standard 802.11, the transmission time drops significantly with the packet loss ratio. This is the effect of the HOL blocking problem: a packet destined to a bad receiver is bound to the channel, thus, the device will keep trying to transmit it until the transmission succeeds or the packet is dropped. However, with $ReDEx$, the aggregate transmission time is less sensitive to the packet loss. The dynamic binding and the weighted scheduling scheme allow the sender to exploit the channel conditions while reducing transmissions to bad neighbors.

B. Effect of Multi Bit Rate

In this section the effect of the multi bit rate is studied. The sender A transmits to B on $11Mbps$ bit rate and to C on $2Mbps$. Table I shows the impact of multi rate on $ReDEx$ and 802.11. In presence of perfect channel conditions, our mechanism achieves a good exploitation of the receiver diversity by increasing the transmissions to node B enhancing thus by 56% the node throughput. Even with 20% packet loss on both links, the gain is still as high as 50%. When the packet loss is diverse, our mechanism succeeds to exploit the more favorable link; in fact the message queue weights that are proportional to the link conditions and the dynamic binding strategy allow the device to affect more channel time to the more favorable neighbor. For example, when the packet loss to C is higher than that to B (third row in the table) the device arrives to allocate even more time to B than in the case of no packet loss. The reason is the message queue weights that reflect the link conditions; higher weight means higher time.

IV. CONCLUSION

In this paper we presented $ReDEx$, a receiver diversity exploitation mechanism to increase the individual throughput of the nodes in the network. $ReDEx$ proposes a modification to the sender side of the 802.11 by employing a per-neighbor message queue and by implementing a scheduler that grants each neighbor a service proportional to its link conditions. The last component of $ReDEx$ is a dynamic binding strategy to cope with the HOL blocking problem. We modeled $ReDEx$ using continuous time Markov chain and showed through Matlab simulations its potentials compared to the standard implementation of 802.11. Our future work consists of extending the evaluation of the mechanism to more complex network scenarios.

Packet loss	ReDEx (Mbps)			802.11 (Mbps)		
$p_C : p_B$	C	B	Agg.	C	B	Agg.
0%:0%	0.737	3.454	4.191	1.342	1.342	2.684
10%:20%	0.814	2.750	3.564	1.287	1.287	2.574
20%:10%	0.572	3.729	4.301	1.287	1.287	2.574
20%:20%	0.660	3.135	3.795	1.265	1.265	2.530

TABLE I

AGGREGATE AND PER-NEIGHBOR THROUGHPUT FOR DIFFERENT TRANSMISSION BIT RATES AND PACKET LOSS RATIOS.

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