An Efficient Opportunistic Cooperative Diversity Protocol for IEEE 802.11 Networks

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ABSTRACT

Opportunistic cooperation promises to enhance the user experience when streaming media over wireless devices by improving wireless network reliability at the link level. This paper presents DAFMAC, an efficient cooperative diversity partner selection algorithm for IEEE 802.11 devices. Simulation results show DAFMAC provides a significantly higher transmission reliability in poor channel conditions than traditional ARQ techniques without modifying the device hardware. Further analysis shows the low overhead of DAFMAC makes it highly competitive with other proposed cooperative retransmission mechanisms in an ad-hoc network.

Categories and Subject Descriptors

C.2.2 [**Computer Systems Organization**]: Computer-Communication Networks - Network Protocols

General Terms

Algorithm, Design, Performance, Reliability

Keywords

MAC protocol, opportunistic cooperative diversity

1. INTRODUCTION

Cooperative diversity protocols [6] have been proposed to mitigate the effects of channel fading in wireless environments. The reliability of point to point links is improved by neighbouring devices cooperatively retransmitting lost data packets. This improvement is passed on to the network and application layers, providing a more stable topology and traffic flow, which is particularly important to mobile streaming media.

While a recent testbed implementation by Bradford *et al.* confirms the predicted diversity gain [3], this work and many others assume an appropriate relay is always available. However, selecting the most appropriate relay from a network is a complex process. Zhao *et al.* proposed a 'nomination round' for relays to indicate their suitability for cooperation [9]. This selection process scales linearly as devices are added to the network and becomes increasingly inefficient as

the size increases. Bletsas *et al.* eliminates the nomination interaction using a 'method of distributed timers' [2]. This method scales well because relays assume link reciprocity to estimate their ability to participate. Overhead is limited to an RTS/CTS transaction and a relay selection feedback flag.

Other protocols are generally based on these two concepts. Lu *et al.* designed and implemented an IEEE 802.11 cooperative MAC layer protocol called PRO [5]. PRO nodes periodically broadcast their link status to nearby nodes to improve the coordination of retransmissions. These broadcasts allow nodes to estimate their cooperative suitability in a distributed fashion to avoid further overhead.

This paper presents DAFMAC - a cooperative decode and forward MAC protocol for IEEE 802.11 devices. It will use existing IEEE 802.11 hardware with a driver modification to coexist with legacy devices. It uses link reciprocity to estimate link quality and a distributed timer scheme to select the best relay. DAFMAC scales well by avoiding inter-relay link status messages.

The contribution of this paper is as follows. The high level relay selection process of DAFMAC described in Section 2. The selection algorithm is developed at the MAC level in Section 3. The simulated performance of DAFMAC is presented in Section 4 with a comparison to 802.11 ARQ behaviour. The cooperative efficiency of DAFMAC is analytically shown to be more efficient than PRO using realistic link estimates in Section 5.

2. PROTOCOL OVERVIEW

The basic principles of DAFMAC are as follows. A source node $\mathcal{S}$ transmits a data frame to destination $\mathcal{D}$, where other nodes are available and in communication proximity of both $\mathcal{S}$ and $\mathcal{D}$. This transmission is overheard and decoded by I potential relays, $\mathcal{R}_i$, $i \in [1, I]$, and stored in a buffer. If $\mathcal{D}$ receives the message, it acknowledges with an ACK packet and the relays flush their buffer. Relays expect to hear an ACK after a SIFS period (T_{SIFS}), as per the IEEE 802.11 MAC standard [4], otherwise they enter a cooperation contention period. The 'best' relay $\mathcal{R}_b$ will transmit first and forwards the data frame to $\mathcal{D}$. Other potential relays hear this transmission and return to idle mode.

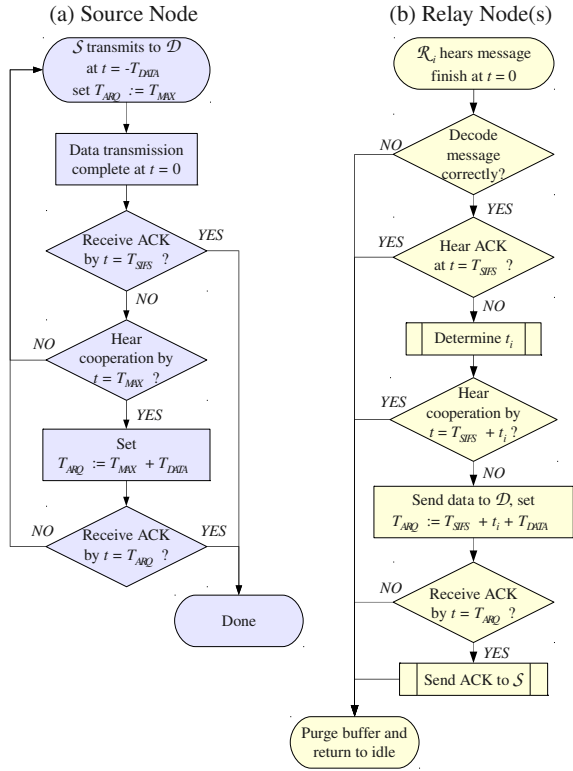Relay $\mathcal{R}_b$ is the relay with the best channel SNR to $\mathcal{D}$,

Figure 1: Operation of (a) the source node and (b) potential relay nodes during a cooperative transmission attempt

Figure 2: A random layout for $\rho_{\mathcal{R}} = 4$; cooperative relays are a subset of nodes and relays are in the interference zone.

given by $SNR_{\mathcal{R}_b \mathcal{D}} \geq SNR_{\mathcal{R}_i \mathcal{D}}$ for $i \in [1, I]$. The channel gain is estimated from the received signal strength (RSS) to $\mathcal{D}$ and the principle of reciprocity. Simulation results show this value is sufficient to select a valid relay even though most 802.11 devices have a low RSS measurement resolution.

The relay selection process uses distributed timers (as used in [2]) where each potential relay will transmit once its timer delay expires. The delay t_i allocated to node $\mathcal{R}_i$ is inversely proportional to the RSS, hence $\mathcal{R}_b$ will have the smallest delay $t_b \leq t_i$. The algorithm to calculate t_i is described in Section 3. All participating nodes reset their timers at the transmission from $\mathcal{S}$.

$\mathcal{S}$ retains the traditional ARQ system in the event that there is no suitable relay. However, it extends the time before ARQ is initiated to $T_{ARQ} = T_{SIFS} + T_{MAX}$, where T_{MAX} is the maximum latency of the cooperative algorithm.

$\mathcal{D}$ transmits its ACK to $\mathcal{S}$ via $\mathcal{R}_b$ if cooperation was used. There is no acknowledgement of the ACK so $\mathcal{R}_b$ assumes the relaying was successful and flushes its buffer when complete. This strategy is validated in Section 4.

Figure 1a shows the actions and states of $\mathcal{S}$ during both direct and cooperative transmissions, whereas Figure 1b shows the behaviour of all potential relays. $\mathcal{D}$ behaves in the same manner as specified in the 802.11 protocol standard [4].

3. PROTOCOL DEFINITION

This section discusses DAFMAC's parameters and how their values are selected.

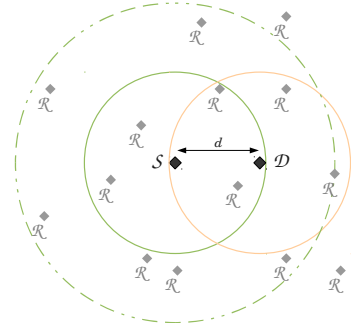The IEEE 802.11 MAC standard defines the maximum transmission range d as the distance at which the probability of sending a 1000 octet message is 0.9 [4]. $\mathcal{S}$ and $\mathcal{D}$ are placed $d_{\mathcal{SD}}$ apart where d is used as the unit of distance. The node density, $\rho_{\mathcal{R}}$, is the number of devices with connectivity to $\mathcal{S}$ other than $\mathcal{D}$. This does not indicate the number of nodes with connectivity to both $\mathcal{S}$ and $\mathcal{D}$ as this would require explicit feedback and introduce overhead. Instead, $\rho_{\mathcal{R}}$ can be determined using the 'neighbour table' in each node and this can be used as a probabilistic estimate of the number of participating relays. An example node placement is shown in Figure 2. The expected practical number of devices in connectivity (ie $\rho_{\mathcal{R}}$) may reach 20 or more in a dense or long range network.

The delay algorithm uses the following parameters:

- T_{SLOT} - one time-slot as defined by the 802.11 MAC.
- T_{MAX} - the maximum range of delay values that t_i can take, measured in units of T_{SLOT}.
- $SNR_{\mathcal{SD}}$ - the SNR from $\mathcal{S}$ to $\mathcal{D}$ such that sending 1000 bytes at distance d has a success probability of 0.9.
- SNR_{OFF} - an offset that determines the minimum link quality of cooperating devices. Relays return to idle unless $SNR_{\mathcal{R}_i \mathcal{D}} \geq SNR_{\mathcal{SD}} + SNR_{OFF}$. Values proportional to $\rho_{\mathcal{R}}$ dynamically regulate the number of participating nodes and significantly reduces collisions.
- SNR_{RNG} - the SNR range (in dB) expected from relays. If $\mathcal{R}_i$ has $SNR_{\mathcal{R}_i \mathcal{D}} > SNR_{\mathcal{SD}} + SNR_{OFF} + SNR_{RNG}$ then it has a stronger SNR than expected and will automatically be allocated delay $t_i = 0$. Otherwise it will have a delay in the range $0 \geq t_i \geq T_{MAX} - 1$.

Both PRO and the 802.11 ARQ use a minimum i.i.d. delay of 0 to 31 T_{SLOT} for collision avoidance. Hence DAFMAC will offer approximately comparable latency and collision avoidance when $T_{MAX} = 32$. The timer delay t_i is generated from $SNR_{\mathcal{R}_i \mathcal{D}}$, as calculated using the RSS and noise measurements already available to the MAC layer. The link budget is the difference in RSS and either receiver sensitivity or ambient noise, although the receiver sensitivity will be the limiting factor in low noise environments. The SNR used is given by

$$SNR_{\mathcal{R}_i \mathcal{D}} = RSS_{\mathcal{D}} - \max(S_{Rx}, N_o) \qquad (1)$$

where S_{Rx} is the receiver sensitivity and N_o is the noise. For example, a RSS of -62dBm with a sensitivity of -88dBm and noise -96dBm would result in a $SNR_{\mathcal{R}_i \mathcal{D}}$ of 26dB.

Relays generate a cooperation rank CR_i by

$$CR_i = SNR_{\mathcal{R}_i \mathcal{D}} - SNR_{OFF} \qquad (2)$$

Algorithm 1 Delay calculation for t_i

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if $SNR_{\mathcal{R}_i\mathcal{D}} \geq SNR_{OFF}$ **then**
  $CR_i \leftarrow \max(SNR_{RNG}-\max(SNR_{\mathcal{R}_i\mathcal{D}} - SNR_{OFF}, 1), 0)$
  if $T_{MAX} > SNR_{RNG}$ **then**
    $T_G \leftarrow \mathrm{flr}(T_{MAX}/SNR_{RNG}) + 1$
    if $CR_i < \mathrm{mod}(T_{MAX}, SNR_{RNG})$ **then**
      $t_i \leftarrow CR_i \times T_G+\mathrm{flr}(\mathrm{rnd} \times(T_G + 1))$
    else
      $t_i \leftarrow T_{MAX}-(SNR_{RNG}-CR_i)\times(T_G-1)+\mathrm{flr}(\mathrm{rnd} \times T_G)$
    end if
  else
    $T_G \leftarrow \mathrm{flr}(SNR_{RNG}/ T_{MAX}) + 1$
    if $CR_i < SNR_{RNG}-\mathrm{mod}(SNR_{RNG}, T_{MAX}) \times T_G$ **then**
      $t_i \leftarrow \mathrm{flr}(CR_i / (T_G) - 1)$
    else
      $t_i \leftarrow T_{MAX}-\mathrm{flr}(SNR_{RNG} - CR_i / T_G)$
    end if
  end if
end if

where: flr - rounds down to nearest integer
  max - selects the maximum value listed
  mod - modulo operation (remainder of integer division)
  rnd - selects an i.i.d. random value in (0, 1)

Table 1: Example delay calculation if $SNR_{RNG} < T_{MAX}$

CR_i	1		2		3		4	5	6	7
t_i	0	1	2	3	4	5	6	7	8	9

Table 2: Example delay calculation if $SNR_{RNG} > T_{MAX}$

CR_i	1	2	3	4	5 6	7 8	9 10	11 12	13 14	15 16
t_i	0	1	2	3	4	5	6	7	8	9

Participating relays have $CR_i \geq 1$ by definition. Algorithm 1 spreads the range of CR values over period T_{MAX} in a quantised piecewise linear function to create timer delay values that favour higher quality links. This algorithm is computationally efficient and does not require any floating point calculations. Tables 1 and 2 show examples of the delay generation algorithm. The top row indicates the CR_i of the relay and the bottom row gives the corresponding delay. A CR_i value may be spread over two or more time slots if $T_{MAX} > SNR_{RNG}$, and t_i is randomly selected from these values. Conversely, several CR_i values may result in the same delay if $SNR_{RNG} > T_{MAX}$.

The RTS/CTS procedure is an option in the IEEE 802.11 MAC protocol to reduce hidden node interference. Xu *et al.* found the RTS/CTS process does not provide significant benefit in ad-hoc environments [8], which is a target application for DAFMAC. Hence DAFMAC can accommodate, but does not require, a RTS/CTS control sequence.

4. SIMULATION RESULTS

This section describes the simulation configuration and compares DAFMAC's performance to the ARQ scheme.

4.1 Network Topology and Configuration

DAFMAC was simulated using a Monte Carlo method in MATLAB. While not as thorough as a test-bed evaluation, it allowed for rapid evaluation of protocol parameter configurations. The results presented are a probabilistic estimate based on 25000 random network topologies where all devices have an omnidirectional radiation pattern, are co-planar and half-duplex with identical physical layer characteristics.

The parameters used in the simulations were $T_{MAX} = 32$, $SNR_{RNG} = 64$ and $d_{\mathcal{SD}} = 1d$ unless otherwise specified. These parameter values provided good cooperative performance with a mean timer delay of approximately $15\,T_{SLOT}$.

A negative value for SNR_{OFF} results in collisions at high node density $\rho_{\mathcal{R}}$ while a positive value resulted in fewer potential relays for low $\rho_{\mathcal{R}}$. Cooperative success is consistently high when $SNR_{OFF} \propto \rho_{\mathcal{R}}$ as shown in Figure 3. Using $SNR_{OFF} = \rho_{\mathcal{R}} - 8$ was experimentally shown to have the best performance for the given parameter set.

4.2 Results and Discussion

Cooperation improves the transmission reliability when $SNR_{\mathcal{SD}}$ is reduced, such as when distance $d_{\mathcal{SD}}$ increases due to node mobility. DAFMAC makes a progressively higher contribution to transmission success as node density increases as shown in Figure 4. While the DAFMAC's probability of success is lower than a direct transmission for $d_{\mathcal{SD}} < 1d$, cooperation will rarely be used in this case because of the high reliability of the original transmission. Beyond $d_{\mathcal{SD}} = 1.05d$, DAFMAC improves the reliability by more than 70% over ARQ for even a low node density. The overall transmission success rate remains high as $d_{\mathcal{SD}}$ increases despite the rapid decline in the reliability of a direct transmission.

The aforementioned parameter values resulted in a mean cooperation latency of about $15\,T_{SLOT}$. This is approximately the same retransmission delay as both PRO and ARQ protocols. Hence, for the same per-transmission delay, DAFMAC offers superior performance to ARQ and similar performance to PRO. Protocol overhead is discussed in Section 5.

DAFMAC provides communication to devices temporarily out of transmission range in a similar fashion to a network layer ad-hoc routing protocol. DAFMAC resides in the link layer of the network stack and uses recent RSS information to estimate an alternate link. Conversely, a routing protocol generally plans the route before transmitting the data. Hence, in the event of an apparent link failure due to a failed direct transmission, the latency of DAFMAC is at least four orders of magnitude lower than the best convergence time of modern proactive routing protocols which may initiate route rediscovery unnecessarily [1]. DAFMAC improves the stability of ad-hoc routing protocols by avoiding intermittent link failures. This is of particular benefit to streaming media where temporary link failures result in severe disruption to the user experience (eg. gaps in audio, frozen or blocky video etc.).

The probability of DAFMAC successfully exploiting cooperation increases with the node density $\rho_{\mathcal{R}}$. However, there are several causes of cooperative failure that limit performance where a 'failure' is an unsuccessful cooperation attempt. The failure modes are: no relays available; relay $\mathcal{R}_b$ has poor link quality; two relays collide; and a hidden relay interrupts the transmission. The mean probability of each failure for random topologies is shown in Figure 5. Please note these results are an average of random node placements and the characteristics of each network will differ.

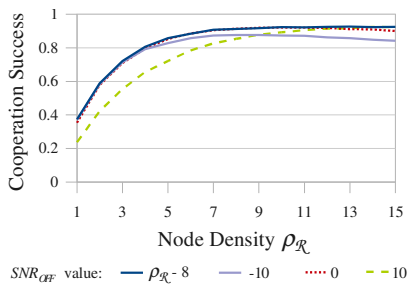The probability of no relay being available decreases as

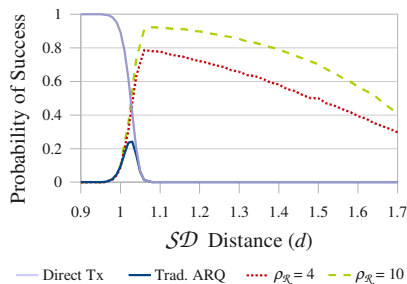Figure 3: Cooperative success can be consistently high when $SNR_{OFF} \propto \rho_{\mathcal{R}}$

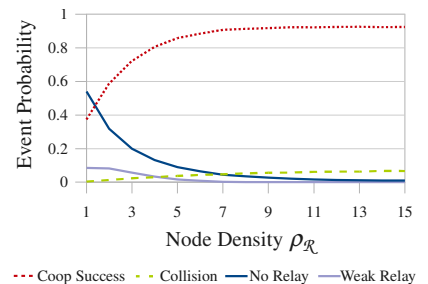Figure 4: The contribution of DAF-MAC is significantly higher than traditional ARQ

Figure 5: The probability of successful cooperation increases with node density despite the collision increase

the node density increases. Decreasing the value of the SNR_{OFF} threshold relaxes the link quality requirement of $\mathcal{R}_b$. However, this correspondingly increases the likelihood that $SNR_{\mathcal{R}_b\mathcal{D}}$ will be too weak for cooperation. The sum of these failures is approximately constant for a range of SNR_{OFF} values, hence this mode of failure is deemed independent of DAFMAC's performance.

A hidden node failure occurs if a relay begins transmitting after $\mathcal{R}_b$ has already started. This will occur when the channel $SNR_{\mathcal{R}_b\mathcal{R}_i}$ is poor, hence they are hidden from one another. The probability that $\mathcal{R}_b$ is close to $\mathcal{D}$ increases with node density $\rho_{\mathcal{R}}$. This reduces the hidden device failure rate because $\mathcal{D}$ is visible to $\mathcal{R}_i$ by definition. The probability of hidden nodes is only significant if SNR_{OFF} is negative (ie. very weak links are used as partners) and is negligible under practical operating conditions.

A collision failure occurs when two relays cooperate simultaneously. The collision probability increases with node density as shown in Figure 5. Relaxing the SNR_{OFF} requirement allows more potential relays and increases the chance of collision. A low SNR_{RNG} value increases the chance of two devices having $SNR_{\mathcal{R}_i\mathcal{D}} > SNR_{\mathcal{S}\mathcal{D}} + SNR_{OFF} + SNR_{RNG}$ and generating a timer delay of 0. Collisions are reduced using $\rho_{\mathcal{R}}$-dependent value for SNR_{OFF}, such as $\rho_{\mathcal{R}} - 8$ in this example, because the link quality requirement increases with $\rho_{\mathcal{R}}$ and limits the number of contending relays. Finally, increasing T_{MAX} reduces collisions at the cost of latency.

The relay selection algorithm favours nodes near $\mathcal{D}$ regardless of $SNR_{\mathcal{S}\mathcal{R}_b}$. Although cooperation will fail if the ACK from $\mathcal{D}$ does not reach $\mathcal{S}$, the simulation showed this was insignificant. If a 1500 byte data frame succeeds with 16- or 64-QAM encoding, a 14 byte ACK using QAM will almost certainly succeed and justifies placing $\mathcal{R}_b$ near $\mathcal{D}$.

5. EFFICIENCY COMPARISON TO PRO

The PRO MAC protocol developed by Lu *et al.* operates in a similar manner to DAFMAC except in the relay selection process [5]. Link quality data is periodically shared with other relays, hence PRO relays have greater knowledge of the network topology than DAFMAC relays. Cooperative collisions in PRO are minimised using a probability sum; once the total probability of a successful link surpasses a threshold, additional relays abstain from cooperation as they are more likely to generate collisions than contribute. Hence PRO effectively avoids collisions at the cost of control packet overhead. The comparison question becomes, is the control overhead in PRO less than the collision loss in DAFMAC?

The PRO overhead is calculated as a transmission sum. Each broadcast contains a T_{DIFS} sense period, a (mean) $15T_{SLOT}$ backoff period, a MAC header and the control data. The data contains the link quality to each node in range and can be compressed into 8 bytes per device. The data length will linearly increase with network density. This process is repeated by all relays within interference range of a node where the interference range is taken as 1.78 times the transmission distance [8]. The *Ohd* column in Table 3 shows the estimated overhead for networks of varying density using IEEE 802.11b at 11Mb/s and 802.11g at 18Mb/s and 54Mb/s.

PRO is assumed to be ideal, with no collisions but with the same losses as DAFMAC for other failure types. Note the DAFMAC collisions require a further retransmission and some of these may fail as well. This forms a geometric sum and this value is used in the loss calculations. DAFMAC is more efficient if the collision loss is less than the PRO overhead. The number of retransmissions required for the losses to become equal (*Tx to Equal* in Table 3) is given by:

$$\text{Tx to Equal} = \frac{\text{PRO overhead}}{\text{Pr(collision)} \times \text{Tx dur.}} \qquad (3)$$

The duration of transmissions for equal loss (*Dur. Tx* in Table 3) is estimated by assuming a 1500 byte data packet at the given rate. This total cooperation period is a 'per second' value and represents a percentage of the total network utilisation. However, this only includes transmission failures that require cooperative retransmission and can estimate the link quality required for the relative losses to match. The *Pr. $\mathcal{S}\mathcal{D}$ Tx* column in Table 3 gives the average $\mathcal{S}\mathcal{D}$ transmission probability for both protocols to have equal losses. The most efficient example of PRO uses IEEE 802.11g at 54Mb/s where the transmission probability is 0.89. Other configurations can only match the efficiency of DAFMAC at lower levels of link quality.

PRO overhead increases at a higher rate than the DAF-MAC loss due to collisions. Hence the $\mathcal{S}\mathcal{D}$ channel must become poorer as $\rho_{\mathcal{R}}$ increases if PRO is to achieve efficiency equal to DAFMAC. This behaviour is shown in Figure 6.

Both protocols are designed for ad-hoc network environments with a network layer routing protocol to ensure link quality. Hence it can be expected that the link reliability will remain above 0.89 and DAFMAC will be more efficient than PRO. Furthermore, PRO will only outperform DAF-MAC in highly saturated networks. Wang *et al.* showed that broadcast control packets become increasingly ineffective for topology control in severely congested networks [7].

Table 3: PRO overhead and performance comparison with DAFMAC for different network configurations

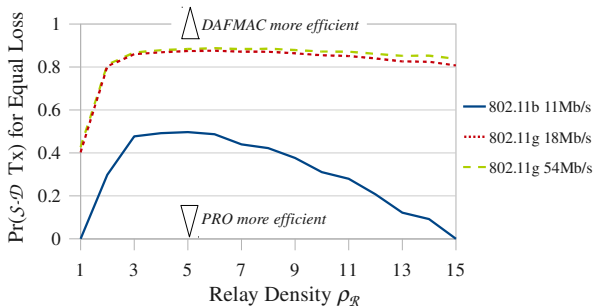| $\rho_{\mathcal{R}}$	Pr($coll$)	802.11b (11M)				802.11g (18M)				802.11g (54M)			
		Ohd (ms)	Tx to Equal	Dur. Tx (ms)	Pr. $\mathcal{SD}$ Tx	Ohd (ms)	Tx to Equal	Dur. Tx (ms)	Pr. $\mathcal{SD}$ Tx	Ohd (ms)	Tx to Equal	Dur. Tx (ms)	Pr. $\mathcal{SD}$ Tx
2	0.0130	9.24	430	702	0.298	2.60	230	198	0.802	2.50	459	190	0.810
6	0.0442	23.2	307	501	0.499	5.60	141	122	0.878	5.09	272	113	0.887
10	0.0606	41.9	398	650	0.350	8.86	160	138	0.862	7.79	310	128	0.872
14	0.0664	65.2	562	918	0.082	12.6	207	178	0.822	10.6	361	149	0.851

Figure 6: The losses for both protocols will be equal at the $\mathcal{SD}$ transmission probability shown - DAFMAC will be more efficient than PRO if the link quality exceeds this value

Therefore, it can be expected that PRO relay selection will also become unstable and result in a high collision rate as network utilisation increases.

This analysis shows while PRO is an established and effective cooperative MAC protocol, DAFMAC should offer more efficient cooperative retransmission under realistic network assumptions.

6. CONCLUSION

This paper presents DAFMAC, a decode and forward MAC protocol that provides opportunistic cooperative diversity for IEEE 802.11 devices without hardware modification.

The protocol, simulated on a simplified model of an IEEE 802.11 device, significantly improves the transmission reliability over a weak channel. These simulations indicate an average improvement in transmission success of more than 70% over ARQ even with low node density while keeping latency approximately the same. Comparison with PRO's control overhead shows DAFMAC is more efficient under realistic network traffic loads and link quality conditions.

DAFMAC will complement existing ad-hoc routing protocols and reduce packet loss. This will reduce costly route re-discovery at the network layer and has the potential to greatly improve wireless network reliability and provide enhanced performance for streaming media.

The simulated results indicate DAFMAC will provide a solid basis for further research, leading to an implementation on commodity IEEE 802.11 hardware. Further simulations will use *QualNet* to evaluate network performance when us-

ing DAFMAC in conjunction with ad-hoc routing protocols and will focus on providing a consistently high quality link for streaming media and other user applications.

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