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Energy, Transmission Power and Data Rate Aware Routing on Mobile Ad Hoc Networks

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Resumo

Modern wireless networks can vary both the transmission power and modulation of links. Existing routing protocols do not take transmission power control (TPC) and modulation adaptation (also known as rate adaptation – RA) into account, even though the performance of MANETs can be significantly improved when routing algorithms use link characteristics to build their routes. TPC unaware routing consumes more energy and increases contention, reducing latency and the throughput of the network. Similarly, RA-unaware routes use low data rate links, increasing the utilization of the medium. This paper proposes and evaluates modifications to routing protocols to cope with TPC and RA. The modifications can be applied to either proactive or reactive protocols that employ cost functions. We present an analytical model of end-to-end energy consumption and latency for multi-hop MANETs, which is used to justify the design decisions taken in our routing extensions. Results show that TPC- and RA-aware routing algorithms can improve the end-to-end throughput by up to 30% and the average latency by up to one order of magnitude, while consuming less energy than traditional protocols.

1 Introduction

Mobile devices are frequently used in situations when there is no infrastructure or the existing infrastructure cannot be used due to catastrophic events. On such situations, the devices organize themselves to form a mobile wireless ad hoc network (MANET). Since the devices operate on batteries, the energy consumed in all tasks, including communication, must be minimized. One way to minimize energy consumption in the communication is to adjust the transmission power. The output power of the transmission is adjusted to compensate the attenuation imposed by the medium while the signal propagates, ensuring that the signal arrives at its destination with the power required to correctly decode the incoming data [16, 1].

Transmission Power Control (TPC) protocols have been studied in two different layers. Several works [1, 16, 10] present MAC-level techniques to dynamically adjust the transmission power. Due to their focus on the MAC layer, measurements are usually limited to a single hop. However, TPC must also be considered on a network level, as the routes must be composed of energy-efficient links. Analytical studies showed that the adjustment of the transmission power can significantly improve the capacity of the network [12], thus several TPC-aware routing algorithms have been created [6, 18, 13].

Existing classic and TPC-aware protocols assume that the data rate of links is constant [6,18], which is not the case in most wireless standards. WiFi and WiMax protocols, for example, adjust the data rate of a link according to the distance between receiver and transmitter, as well as to environment noise and interference. This dynamic adaptation, known as Rate Adaptation (RA) [15, 20], affects the time required for a packet to be transmitted as well as the reception probability of a packet, since it defines how much data is transmitted in a single time unit, frequency channel or code. Modulations that carry more data at a time are said to be more *spectrally efficient*. An increase in spectral efficiency usually requires a higher signal to noise ratio (SINR) to allow the correct decoding of data, and thus more spectral efficient modulations will usually require a stronger transmission power or a medium with less interference.

Furthermore, RA and TPC cannot operate independently. If we reduce the transmission power of a link without considering the modulation employed, we may reduce its data rate, or even prevent packets from being received. Likewise, if the rate adaptation algorithm changes the modulation without considering the transmission power, packet transmissions may consume more energy than necessary, or packets may not be received at all. Thus, some works proposed joint rate and transmission power adaptation at the MAC layer [25, 2]. The problem, however, has been overlooked in existing routing protocols. To build efficient routes, protocols must take into account the maximum data rate of each link as well as the required transmission power to achieve this data rate. Otherwise, routing may build paths that provide a poor throughput and consume too much energy. Although there are some analytical models showing the performance of networks with dynamic modulation and transmission power [5,27,30], to our knowledge there are no TPC- and RA-aware routing protocols for CSMA/CA based networks.

In this paper we approach the problem of TPC- and RA-aware routing. We propose extensions to existing routing and MAC protocols, in order to build TPC-aware routes that take links with different data rates into account. These modifications are quite simple and generic, and hence are applicable to most MANET routing and MAC protocols. Since the problem of TPC is inherently cross-layer, we instantiate such modifications over DSDV and IEEE 802.11, with the support of a middleware called MANKOP [23]. The middleware eases the sharing of information among the diverse protocols residing on the nodes, thus providing a simpler and more modular implementation. We support our decision to minimize hop count and maximize the data rate at each link using an analytical model of the end-to-end energy consumption and latency of a flow in MANETs. This model takes into account medium contention and the characteristics of power consumption and rate of each frame of the IEEE 802.11 standard, showing that the routing decision to minimize energy consumption (a very common choice in MANET routing) seems to perform worse than minimizing hop count when links use both TPC and RA algorithms. Finally, we used simulations to compare our solution against ClusterPOW [18] and CONSET [6] TPC-aware protocols, and a standard version of DSDV. Results show that TPC- and RA-aware routing can improve throughput, energy consumption, and latency of flows.

The rest of this article is organized as follows. Section 2 presents the related work. Section 3 reviews the technical background behind adaptive modulation and transmission power control in MANETs. Section 4 shows our modifications to support TPC and RA. An analytic model for the average end-to-end energy consumption and latency in MANETs is presented in Section 5. Section 6 shows the simulation setup, followed by the results and their analysis in Section 7. Section 8 presents the conclusions and future work.

2 Related Work

The benefits of TPC on multi-hop wireless networks have been analytically studied by Gomez and Campbell [12]. They showed that per-link range adjustments outperform global range transmission adjustments by 50%. Further, the average per node traffic capacity is constant even if more nodes are added to the network when TPC is used. Meanwhile, the capacity decreases as more nodes are added on networks with a fixed transmission power. Others studied the capacity of networks using TPC- and RA-aware links by means of optimization models [5,27,30]. Zhai and Fang use conflict graphs, coupled with SINR calculations and packet transmission times under different modulation schemes to identify which nodes can transmit at the same time, and at which data rate, given that the transmission power is fixed [30]. Those works intend to model the capacity of the network (the maximum throughput of the network), while we are interested in this work in the end-to-end latency and energy consumption of the flows.

A number of TPC techniques for the MAC layer have been proposed [1, 16, 10, 22]. Those are either iterative, where the transmission power is dynamically adjusted to keep a constant link quality [10], or instantaneous, where calculations are employed to identify the ideal transmission power at each individual packet [1, 16, 10, 22]. Being MAC-layer solutions, they are limited to a single hop and focus only on energy consumption, ignoring end-to-end latency and throughput. The same happens to rate adaptation, which has a plethora of adaptation protocols based on the MAC layer [15, 20]. To our knowledge, there are no RA-aware routing protocols for MANETs based on CSMA/CA MAC protocols, and the only existing routing protocol for TDMA networks cannot be applied to CSMA/CA networks [21].

Both TPC and RA techniques must operate in tandem in real networks. Any of the existing RA-aware protocols consider that we could increase the transmission power to maintain the data rate, while no work on TPC considers that reducing the transmission power can reduce the data rate of a link. Most works in TPC and RA are focused on single hop measurements, while there is a need to understand the effect of both techniques in multi-hop scenarios. Currently there are only MAC level protocols that consider this synergy. MiSer is a MAC-level adaptation protocol that chooses the best modulation and transmission power according to the number of transmitting stations, packet length, SINR at the receiver as well as the contention on the network [25]. The protocol requires the solution of recursive equations, where the number of stations, a propagation model and a collision probability must be provided to solve the model. Thus, the protocol cannot adapt its behavior to a variable number of stations. Akella et al. propose extensions to classic rate adaptation algorithms to take the transmission power into account in the context of structured WLANs [2].

Routing protocols in the literature consider only TPC or RA at a time [30,6,18,13]. We will focus below on the most important proactive solutions, since this article proposes a proactive routing solution for TPC and RA.

The CONSET protocol presents a MAC-level solution to TPC-aware routing [6]. The rationale behind CONSET is that routing protocols try to minimize the number of hops. Thus, MAC protocols should limit the "neighborhood" of a node to only those necessary to keep each node connected, making routes more energy-efficient by using only low-power links. Although the work presents results for IEEE 802.11 MANETs, the authors did not model the dynamic variation of modulation. Further, since the method relies on control packets to identify the neighborhood, it may select links with the lowest data rates, once such packets are sent at the basic data rate on WiFi. Kawadia and Kumar proposed ClusterPOW and other TPC-aware routing protocols to reduce the energy consumption of MANETs [18]. Those protocols execute several instances of a routing algorithm, one for each available transmission power. Each instance calculates its routes independently, and the route chosen to forward data is the one which employs the smallest transmission power level. This strategy demands a high amount of energy due to the execution of several instances of the routing algorithm. Further, their protocols do not support multiple modulations.

3 Background

This section gives an overview of adaptive modulation and transmission power control. We include this section because the comprehension of our work requires the understanding of both technologies as well as their impact on MANETs. Further, the integration of RA and TPC produces interesting interactions, increasing the issues that must be dealt by routing algorithms.

3.1 Rate Adaptation

The WiFi and WiMax standards, among others, perform rate adaptation [29] to cope with interference and bad links. If the reception is good and the signal arrives with a high power at the receiver, then the sender codes the data using modulation schemes that can carry more data. However, if the signal quality is not good due to interference or due to a weak signal at the receiver, the sender uses modulations more resilient to interference. Resiliency, in this case, implies in a lower spectrum efficiency, reducing the data rate. Besides varying the data rate, rate adaptation influences the occupation of the medium, as frames transmitted at a lower data rate will demand longer transmission times.

Rate adaptation is well-known to users of structured WiFi networks. Stations near the AP will most likely transmit at higher bandwidth, e.g. 54Mbps on 802.11g, while distant ones will transmit at lower bandwidths, e.g. 6Mbps. This change occurs because modulations having lower data rates require a lower signal to noise ratio (SINR), which is the difference of the power of the signal when compared to interference and thermal noise (See Table 2 on Section 6 for the SINRs of a real radio). As a consequence, frames transmitted using lower data rates will have a larger range. Wireless standards that use rate adaptation do not specify a rate adaptation algorithm, thus each vendor employs its proprietary solution.

3.2 Transmission Power Control in Wireless Networks

Transmission Power Control (TPC) protocols adjust the transmission power to minimize energy consumption. Whenever a station has data to transmit, it does so at the lowest transmission power necessary to reach the destination, consuming less power when compared to a fixed power configuration. TPC also reduces collisions and increases network capacity [12].

TPC algorithms adjust the transmission power in a way that the frames arrive at the receiver with a strength that guarantees an acceptable SINR. The ideal transmission power of a link can be estimated either using calculations or using a closed control loop [10]. In the former, nodes measure the transmission and reception power of control frames, as well as the average noise in the medium. With this information, they determine how much the signal degrades when traveling from sender to receiver, and adjust the transmission power accordingly. Another solution is the use of a control loop, in which nodes monitor the packet drop rate of the link. Whenever it is higher than a certain threshold, the sender slightly increments the transmission power. Similarly, if the drop rate is low, the sender gently decrements the transmission power.

RA influences TPC, as each modulation requires a different signal to noise ratio, which increases with the data rate (See the values on Table 2 for a real example). Thus, in order to have a higher data rate, the packet must be transmitted using a higher transmission power. TPC algorithms can improve the operation of networks using rate adaptation. Take, for example, the situation in which the data rate decreases as the sender and receiver move away from each other. Using TPC, we could increase the transmission power to compensate the attenuation caused by the increase in distance, maintaining a higher data rate. Further, applying TPC together with RA increases the capacity of the network as frame transmissions take less time.

3.3 Transmission Power Control and Rate Adaptation over IEEE 802.11

The IEEE 802.11 standard defines that control frames (RTS, CTS, ACK), preamble and broadcast frames must be transmitted at the basic rate (in 802.11b, this means 1Mbps), while unicast frames may be transmitted at any of the available data rates. As a consequence, broadcast messages will reach more nodes than unicast messages, because lower data rates employ a modulation scheme that is decodable by farther nodes or by nodes on noisier environments. The effect above directly influences routing, once most protocols rely on broadcast messages [3]. The problem arises because any node that answers to the route advertisement messages is considered as a suitable route. Further, all links are considered to have the same data rate, leading to a degraded throughput, as exemplified below.

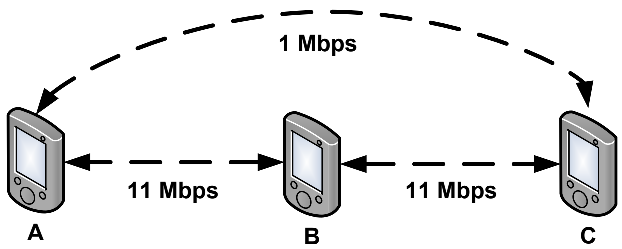

Figura 1: An example of the influence of rate adaptation in routing.

Figure 1 illustrates the effect of RA on routing. Suppose that node A wants to build a route to node C. It communicates directly with C at 1Mbps. However, node B can communicate with both A and C at 11Mbps. In a classic routing algorithm minimizing hop count, node A would send a `HELLO` message to determine its neighbors. This message is be picked up by both B and C, and the algorithm chooses to transmit directly, as this decision minimizes hop count. However, the route passing by B has a higher throughput.

We cannot send the `HELLO` message at 11Mbps to avoid links with low data rates, thus routing should explicitly consider the data rate of the links. Another solution is to use TPC to increase the data rate whenever possible. Hence, the best solution is to marry TPC and RA, so TPC improves the data rate of links when possible, and routing algorithms favors faster links when building their routes.

4 TPC and RA-Aware Routing Over MANETs

This section presents our TPC- and RA- aware routing extensions for MANETs. Our solution has two parts, the transmission power calculations considering RA (detailed in Section 4.1) and the construction of routes based on the energy consumption and data rate of each link (presented in Section 4.2). The proposed solutions require the cooperation of routing, MAC and physical layers, thus our implementation uses a middleware for information sharing over MANETs, called MANKOP (MANet KnOwledge Plane) and is described in Section 4.3, along with its use on TPC-aware routing with RA.

4.1 Assessing the Ideal Transmission Power and Modulation

Existing MAC-level methods for the calculation of the transmission power and modulation are applied to one link at a time [1, 16, 10, 22, 20, 15], which is not sufficient for our needs due to a lack of scalability. A routing protocol requires the knowledge of the minimum transmission power and data rate for *all* nodes beforehand, thus this process cannot be done individually. Another approach is presented by Kawadia and Kumar, in which nodes send beacon packets at different transmission powers [18]. The ideal transmission power of a node is defined by the beacon with the smaller transmission power that was correctly received. This alternative cannot be extended to take RA into account, since we cannot change the modulation of broadcast packets to match that of unicast packets.

Thus, we decided to enhance MAC-level TPC calculations to identify the transmission power and modulation at the same time for more than one link. This algorithm assesses the probable modulation and transmission power used on each link. We assume that another algorithm, e.g. AARF, RBAR or others, will adjust the transmission power and modulation on each link in real-time. This strategy provides more fine grained adjustments, since unicast rate and TPC adaptation algorithms operate at a per packet granularity. Meanwhile, the proposed algorithm must run less often due to the use of broadcast messages.

Figure 2 shows how we can identify the transmission power and modulation for several nodes at the same time. Suppose that nodes A, B and C wish to identify the transmission power and modulation from one to the other. Initially, they know nothing about themselves. First, nodes broadcast a message using a known (or informed) transmission power and modulation.

This message will be used by the others to calculate the minimum transmission power and maximum modulation from the sender to themselves. The transmission power employed is stored in the payload of the message, as all the other values which we will refer to below. In the figure, nodes A, B and C send broadcast messages. Note that the three first messages have an empty transmission power table (an empty gray box). This message is used to calculate the transmission power and modulation from the sender to the receiver using the calculations described later. Take, for example, the message broadcasted by node B. Node A will calculate and store ($C\&S$ in the figure) the best transmission power and modulation from B to A, while node C will calculate and store the best transmission power and modulation from B to C, using the method explained in the following. The next message from A will contain P_{BA}, M_{BA} and all the other calculated transmission powers and modulation pairs on its payload, thus when node B receives the message from A, it will store P_{BA}, M_{BA} (S P_{BA}, M_{BA} in the figure). Further, after the second broadcast, all nodes should know the ideal transmission power and modulation to reach their neighbors. In order to calculate the link parameters for the highest number of nodes at the same time, nodes broadcast their messages using the maximum transmission power of the radio.

The recalculation interval must be a function of network mobility pattern of the network, in order to avoid frequent transmission power fluctuations. If nodes move too fast, the approximated transmission power and modulation may not be up to date when disseminated. Thus, we assume that the update interval is frequent enough to cope with node mobility.

Our second contribution is the adaptation of the existing transmission power calculations [16, 1, 10] to consider the modulation. Usually, those methods use the base formula[1] $P_{TxMin} = (N + I)SINR_m G_{ij}$, where $N + I$ is the signal and interference at the receiver, $G_{ij} = \frac{P_{RX}}{P_{TX}}$ is the path loss and $SINR_m$ is the SINR for modulation m (usually fixed). As explained in Section 3.1, each modulation has its own signal to noise ratio. Thus, we apply the equation above to calculate for every possible modulation in order to identify the maximum data rate, as explained below.

The developed solution, presented in Algorithm 1, works as follows. We start by calculating the required transmission power for the highest data rate using the lowest transmission power. If the calculated transmission power is feasible (that is, if we send a packet using a transmission power supported by the radio and the reception power provides an acceptable signal to noise ratio), then the process stops. If not, we increase the transmission power

[1]Some parameters were omitted for simplicity reasons. Please refer to [10] for a complete description of the calculation.

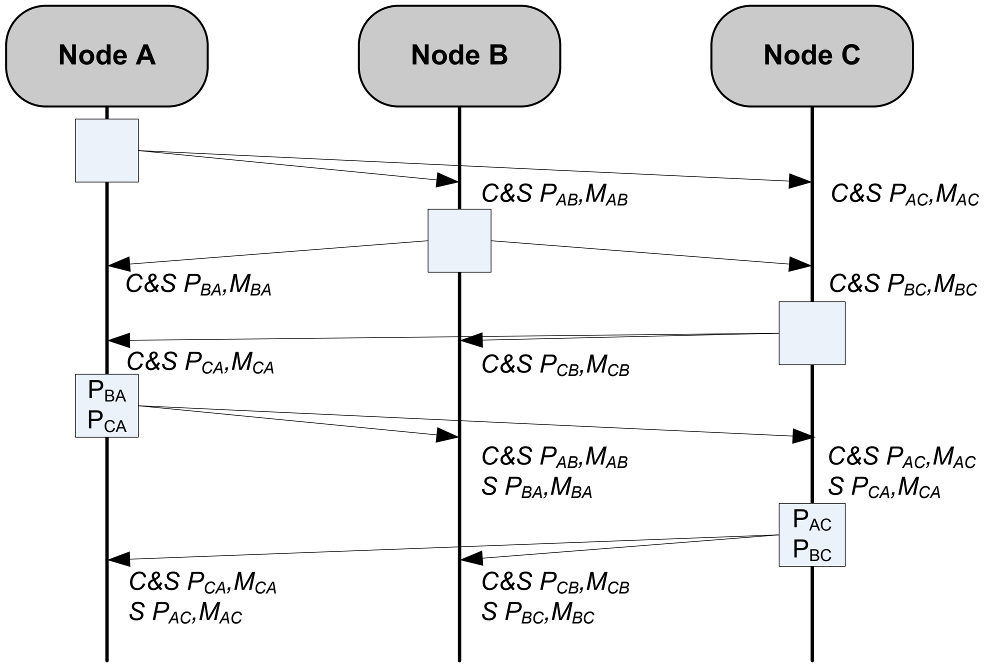

Figura 2: Message dialogue used to calculate the minimum transmission power and modulation for several links at the same time.

up to the maximum transmission power of the radio. Next, if the highest data rate is not achievable, we reduce the tentative data rate and reapply the equation with its associated SINR. The process repeats until a valid transmission power is found or all the data rates and transmission powers are tried. This algorithm is fast, as the number of transmission power and data rate combinations is usually lower than fifty.

Unlike unicast TPC and RA algorithms, which use instantaneous noise, interference and gain values, our calculations employ averaged values. This is because we want to capture the *medium-term* behavior (e.g. the behavior within seconds to a minute) of the link, in order to provide a stable route. Unicast algorithms, on the other hand, may change the PHY configuration for each packet to cope with movement and fast fading, and thus can optimize their decisions to short term variations, e.g. within each frame. However, we cannot use those methods to assess the overall quality of the link within longer time periods. This is why we advocate to separate rate and transmission power adaptation from routing decisions.

Since the calculation of the transmission power requires periodic message broadcasts, our solution is not recommended for WSNs or MANETs when the amount of traffic is low. In such networks, data transmissions are rare,

Algorithm 1 Finding the transmission power with RA.

function $calculateTxPowerDataRate(P_{TX}, P_{RX}, Noise)$
  $gain \leftarrow \frac{P_{RX}}{P_{TX}}$;
  for $rate \leftarrow 11Mbps$ **downto** $1Mbps$ **do**
    for $txpow \leftarrow minTxPow$ **upto** $maxTxPow$ **do**
      if $SINR(gain, pot_{txpow}, Noise, Interference) > SINR_{rate}$ **then**
        return $[txpow, rate]$;

thus nodes stay silent or dormant for most of the time. In such a situation, periodic messages would significantly increase the energy consumption of the network, and dormant nodes would not participate in the calculation. Thus, the calculation should be performed on demand, as we plan to explore in future work.

4.2 Building TPC- and RA- Aware Routes

Besides calculating the ideal transmission power and modulation of each link, the RA- and TPC-aware solutions require adaptations in the routing minimization strategy. Assuming that the routing algorithm minimizes a certain cost over the links, as it is the case for most algorithms [3], the link cost and the cost minimization function must be adapted as follows. The cost of a path (P_{ij} in our notation, the set of links traversed) is defined as a tuple $[datarate, length, energy]$, where:

$$\begin{aligned} &datarate = min(datarate_p)\ \forall p \in P_{ij};\\ &length = |P_{ij}|;\\ &energy = \sum_{P_{ij}}^{p} P_{TXp}; \end{aligned}$$

The parameter *energy* (the energy consumed for sending a byte over the link) is the transmission power used in each link. Both *energy* and *datarate* come from the calculations described in Section 4.1. Finally, the minimization function of the routing algorithm should minimize $min(\frac{1}{datarate}, length, energy)$, which first maximizes the data rate, then minimizes route length and energy consumption. Note that we take an approach that is different from most routing algorithms for MANETs. As we will show in Section 5.2 and in the simulations, minimizing hop count seems to perform better than minimizing energy consumption on links with dynamic data rates and transmission powers.

Once we do not change the messages exchanged by the routing protocols, only its internal cost function, such a modification could, in principle, be applied to any existing routing protocol, proactive, reactive or geographic, as long as it works by minimizing a cost function. The data rate and transmission power do not exclude the use of other parameters, such as link reliability, degree of security of links, among others, in the cost minimization function.

4.3 Integrating MAC and Routing

The proposed models require the cooperation of routing, MAC and physical layers, thus we should employ cross-layering middlewares such as MANKOP [23] to produce a more modular implementation. Such middlewares expose data interdependencies among protocols, which allows the replacement of an entire protocol by another as long as the concerned protocols adhere to pre-defined interfaces and data conventions dictated by the service (in this case, TPC- and RA-aware protocols). The proposed modifications could also be implemented directly over the protocols. However, this strategy could produce a less modular and maintainable implementation due to implicit dependencies and a lack of clear separation of concerns [17].

MANKOP (MANet KnOwledge Plane) is a middleware for MANETs that simplifies the sharing of information among protocols, applications and services [23]. This middleware implements a distributed knowledge base, where each node stores knowledge concerning itself and the nodes in its neighborhood. MANKOP is used for two functions in this work. First, we aggregate control data from PHY, MAC and routing layers using a single MANKOP message, reducing the load in the network. Second, we use MANKOP to store shared information, such as the gain, the transmission and reception powers and the energy consumed in each link. Finally, we also profit from MANKOP events to identify nodes leaving the neighborhood to automatically trigger route reconstructions.

Algorithm 2 summarizes the interaction of IEEE 802.11 and our enhanced version of DSDV (called DSDV-TPCA) with MANKOP. Whenever a MANKOP packet arrives, the MAC layer calculates the ideal transmission power. In order to do so, it accesses the radio to obtain the reception power of the packet. Next, the ideal transmission power and modulation are stored in MANKOP. The MAC layer also updates the last time a packet coming from this node has been seen. This information is used by the function `purgeOldTxPwr` to create MANKOP events when a node is unreachable. This function verifies if packets (routing, data, or control) have not been received from this node for a pre-specified amount of time. Whenever this happens, the MAC layer generates a MANKOP event that is subscribed by the routing

Algorithm 2 Interaction of protocols with MANKOP.

```
class 802.11
   function arrivingPacket(P)
      RxPower ← Kplane.getRxPwr()
      Kplane.TxPwr ← calculateTxPwr(P.TxPwr, RxPwr, P.dataRate)
      lastPacket[P.address] ← time()
   function purgeOldTxPwr( )
      foreach n in lastPacket do
         if time() − MAXIMUM_LIFETIME > n then
            Kplane.changedState(n, UNREACHABLE)
class DSDVKP
   function arrivingPacket(P)
      updateRoutes(P)
   function kpChange(event, nodeAddress)
      if e = UNREACHABLE then
         invalidateRoutes(nodeAddress)
```

layer, which invalidates all routes that depend on the unreachable neighbor and schedules route updates upon each newly received event.

5 Analytical Model

This section presents an analytical model for the average end-to-end energy consumption and latency of multi-hop networks with multiple transmission powers and multiple modulation schemes. This model corroborates our decision of using high data rate, low hop count routes, by comparing this strategy against low energy, high hop count data rates. Before we begin, we present in Table 1 the nomenclature used in the formulas presented in this section. Uppercase letters indicate the type of the variable, subscripts indicate their subtype and superscripts provide parameters for this type. There are two different representations for power: P, which denote the output power for transmission/reception of signals in the transceiver, and E, the total power consumed for a given operation.

In order to make the modeling of packet transmission tractable, this model requires several assumptions. First, radio propagation is assumed to be isotropic and it does not change in time. Nodes are static, and are deployed randomly in the area[2]. We assume that there are enough nodes such that

[2] We do not model mobility due to the lack of good mobility models, as well as to the fact that the reaction to link breaks will vary wildly depending on the routing protocols.

Symbol	Meaning	Unit
D	signal range	meters
E	consumed energy	joules
λ	packet arrival rate per slot	packets/second
L	payload length	bits
P	output/input signal power	Watt
R	data rate	bps
W	Maximum number of slots of the first contention dispute (CWMin)	slots
T	time	seconds
δ	node density	nodes/m^2
H	Number of hops	N/A
$\mathcal{P}$	probability of an event	N/A
$\mathcal{R}$	ratio of two signal powers	N/A
p	Transmission power of data frames	N/A
m	Modulation used for the transmission of data frames	N/A

Tabela 1: Notation used in the analytical model

we can always find a possible forwarder within the limits of the propagation range of the payload. We also assume that the back-off is a memoryless process. Finally, we consider that the transmission time of the control frames (RTS, CTS, ACK) is fixed. However, in recent wireless standards those frames can be transmitted using different modulations, yielding faster transmission times. Our model could be easily extended to support variable modulation in control packets, but we did not address this issue since it is out of the scope of the article.

The end-to-end delay and energy consumption of a node is a function of the per-hop delay and the number of packet forwards. The number of packet forwards as well as the per-hop delay depends on the transmission power, p, and the modulation, m. Thus, we can express the end-to-end delay and energy consumption as below, where $E2E$ stands for end-to-end.

$$T_{E2E}^{(p,m)} = T_h^{(p,m)} \times H^{(p,m)} \tag{1}$$

$$E_{E2E}^{(p,m)} = E_h^{(p,m)} \times H^{(p,m)} \tag{2}$$

The number of hops traversed in a path from nodes i to j will depend on the signal range and the amount of interference. In wireless networks, frames are received if the incoming signal, attenuated by a certain gain ($\mathcal{R}_G$), is higher than a certain signal to interference and noise ratio ($\mathcal{R}_{SINR}$) defined by the modulation of the data. $\mathcal{R}_{SINR}$ is a function of the thermal noise of the environment (P_{Noise}) and the received strength of other transmissions, which form the interference set I. Finally, frames must arrive at the receiver at a strength superior to the carrier sense threshold, P_{CS}, which is the smallest power with which the radio can reliably decode signals.

We need to know the interference level of *all* stations in order to determine if a packet will be correctly received, thus requiring the knowledge of their precise location. Thus, we use in this work a distance-based reception model, where the reception of a packet is based on the assumption that no other station is transmitting at the same time. Based on this model, each modulation will have its own reception threshold:

$$P_{RXThresh}^{(m)} = max(P_{Noise} \times \mathcal{R}_{SINR}^{(m)}, P_{CS}) \tag{3}$$

In this situation, we can apply a known propagation model to calculate the maximum distance over which nodes correctly receive packets. One such model is the *Two Ray Ground* model [26], where the signal is assumed to degrade with the inverse power of α, where $\alpha \geq 2$ is defined by the type of the environment. Further, the maximum propagation distance can be calculated as shown in Equation 4, where β is a constant based on the characteristics of the transceivers and the antennas.

$$D_{MAX}^{(p,m)} = \sqrt[\alpha]{\frac{\beta \times P_{TX}^{(p)}}{P_{RXThresh}^{(m)}}} \tag{4}$$

If we assume that the network is dense enough so that nodes will always find another node to forward to at the maximum reception range, the number of hops used to traverse the distance between source and destination, D_{E2E}, will depend on the maximum reception range, as shown in Equation 5.

$$H^{(p,m)} = \left\lceil \frac{D_{E2E}}{D_{MAX}^{(p,m)}} \right\rceil \tag{5}$$

Next, we will show how to calculate the per-hop energy consumption and latency. There are two main components that must be taken into consideration, which are contention and the interference. Contention will make transmissions require more retries, since transmissions will collide more often due to more stations trying to transmit at the same time. Also, contention increases the waiting time necessary to transmit a packet because other stations may start to transmit before a given station tries to secure the medium. Interference, on the other hand, will influence the probability of correctly receiving a frame and the maximum transmission range. In this work we only model contention, leaving interference for future work. In the next section we show how to approximate medium contention.

5.1 Modeling Contention

Before describing how contention is modeled, we must first show how the IEEE 802.11 back-off mechanism works. Before transmitting data, each station chooses a random value $1 \leq B \leq CW$ as its back-off. Time is slotted, and a station will transmit only *after* it has sensed B *idle* slots. Thus, the counter is frozen whenever a station senses that the medium is busy. If, after the back-off counter is zeroed, the station transmits and a collision occurs, the station tries to retransmit after another random number of slots, now in the interval $[1, 2CW]$. The maximum number of slots doubles after each collision up to $CWMax$. Finally, the maximum number of retransmissions is limited.

We assume that time is slotted, and each station transmits with a certain probability at each slot. The duration of the slots varies, representing collisions and successful transmissions [7]. In this model, the contention on IEEE 802.11 networks using the Distributed Coordination Function (DCF) mode is modeled using Markov chains. This model assumes that nodes transmit with a constant probability in each slot, and that the packet inter-arrival time follows a poisson distribution[3]. This model does not take queueing delays into account, thus it would represent the stationary state of a network where there are no queue build-ups.

As defined in [7], the probability that a station transmits at a random time, τ, is given by equation 6, where $\mathcal{P}_c$ is the collision probability, W is the size, in symbols, of the initial contention window of 802.11 and m is the number of "back-off stages", that is, the maximum number of allowed back-offs.

$$\tau(\mathcal{P}_c) = \frac{2}{1 + W + P_c \times W + \sum_{i=0}^{m-1} (2\mathcal{P}_c)^i} \tag{6}$$

The collision probability is calculated as a function of the probability that a node will transmit in one slot, λ, as well as the number of nodes, as shown below. Further, we also define the probability of a correct transmission ($\mathcal{P}_t$, where only one station acquires the medium at a given slot) and the probability of an idle slot ($\mathcal{P}_i$):

[3]This formula assumes that the packet arrival process is memory-less, which is not the case in real networks, e.g. due to higher-level packet retransmissions in TCP. However, results in [7] show that this model is a good approximation of the performance of real WLANs.

$$\mathcal{P}_t = \lambda(1-\lambda)^{N-1} \tag{7}$$
$$\mathcal{P}_i = (1-\lambda)^N \tag{8}$$
$$\mathcal{P}_c = 1 - \mathcal{P}_t - \mathcal{P}_c \tag{9}$$

It is known, however, that different transmission powers affect the number of stations that will have to contend for the medium. We add this effect to the formulas by varying N, the number of stations contending for the medium. Assume that nodes are uniformly distributed in the area, with density δ nodes per unit of area. Hence, the number of nodes covered by any given transmission, $N^{(p)}$, will depend on the maximum carrier sense range, as shown in Equation 10.

$$N^{(p)} = \delta\pi \times \left(D_{CS}^{(p)}\right)^2, \text{ where } D_{CS}^{(p)} = \sqrt[\alpha]{\frac{\beta \times P_{TX}^{(p)}}{P_{CS}}} \tag{10}$$

As a side note, equation 10 states that the number of blocked stations *does not depend* on the modulation of the payload, while the correct reception of the frame *does*. Further, the number of possible packet forwarders is *smaller* than the number of blocked stations due to the transmissions of this packet.

Once we have the probability of transmission at a given slot, we know that the average number of slots required for a station to transmit is τ^{-1}. Further, the station will have to wait, on average, $\tau^{-1} - 1$ slots before transmitting. Out of those, $(\tau^{-1}-1)\mathcal{P}_i$ will be idle, because all stations still have a non-zero contention counter; $(\tau^{-1}-1)\mathcal{P}_c$ will result in collisions and $(\tau^{-1}-1)\mathcal{P}_t$ will be transmissions of other stations. The average one-hop delay and energy consumption can then be modeled as below:

$$\begin{aligned} T_h^{(p,m)} = {} & (\tau^{-1}-1)(\mathcal{P}_c \times T_c^{(m)} + \mathcal{P}_t \times T_s^{(p,m)} \\ & + \mathcal{P}_i \times T_{slot}) + T_s^{(p,m)} \end{aligned} \tag{11}$$

$$\begin{aligned} E_h^{(p,m)} = {} & (\tau^{-1}-1)(\mathcal{P}_c \times E_c^{(m)} + \mathcal{P}_t \times E_t^{(p,m)} \\ & + \mathcal{P}_i \times T_{slot} \times E_i) + E_s^{(p,m)} \end{aligned} \tag{12}$$

Equations 11 and 12 depend on the definition of the energy consumption and latency for collisions, the correct transmission of a packet by other stations and the correct reception of a packet. We differentiate energy consumed by the correct transmission of a packet by a given station (E_s) from the

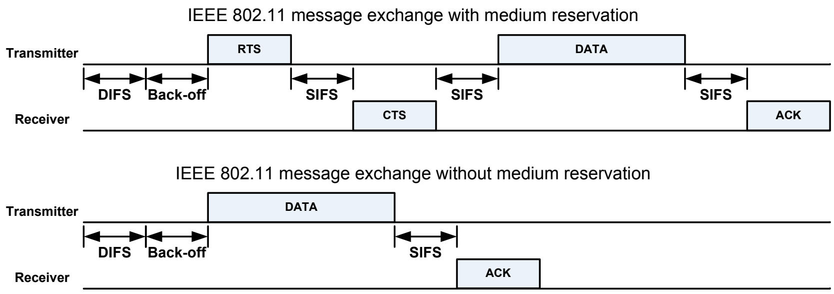

Figura 3: Message exchange in the IEEE 802.11 standard.

energy consumed when other stations transmit (E_t). E_s models the energy consumed by the station that is sending the packet, while E_t models the energy consumed by a station listening to the packet.

Figure 3 shows a diagram of the message exchange of IEEE 802.11 stations. As defined in the standard, there is an obligatory idle interval of T_{SIFS} between frames of the same dialogue, that is, the frames involved in the transmission of one data frame. For frames from different dialogues, the idle time (T_{DIFS}) is larger. Stations not participating in a dialogue are only allowed to send their data after the medium has been idle for a time interval of T_{DIFS}.

The successful transmission time and energy consumption of a frame when no transmissions occur are described by equations 13 and 14. We assume that the transmission time of all control frames already includes the preamble, while we separate the calculation into preamble and payload for the data frame in order to cope with the different modulation strategies. We count one propagation time, T_ρ, for each frame sent or received.

$$\begin{aligned} T_s^{(m)} &= T_{DIFS} + T_{RTS} + T_{CTS} + T_{preamble} + \frac{L}{R^{(m)}} \\ &\quad + T_{ACK} + 3T_{SIFS} + 4T_\rho \end{aligned} \tag{13}$$

$$\begin{aligned} E_s^{(p,m)} &= (T_{RTS} + T_{preamble} + \frac{L}{R^{(m)}}) \times E_{TX}^{(p)} \\ &\quad + (T_{CTS} + T_{ACK}) \times E_{RX} \\ &\quad + (T_{DIFS} + 3T_{SIFS} + 4T_\rho) \times E_{idle} \end{aligned} \tag{14}$$

In both equations we assume that the transmission power of the frames is the same as the preamble. Each unsuccessful transmission will incur in energy and delay penalties, which are given by the equations below without medium reservation. The rationale behind those equations is that a frame must be transmitted, and then a timeout period (T_{DIFS}) must expire. Within this period, the receiver can be in idle for T_{SIFS}, while for a period of $T_{DIFS} - T_{SIFS}$ the station will stay in reception mode, waiting for the reception of a CTS. With medium reservation, collisions would occur only on the RTS packet, thus the delay to identify an unsuccessful transmission will be smaller, since:

$$T_c = 2T_{DIFS} + T_{RTS} + 2T_\rho \tag{15}$$

$$\begin{aligned} E_c^{(p)} = T_{RTS} \times E_{TX}^{(p)} + (T_{DIFS} + T_{SIFS} + 2T_\rho) \times E_{idle} \\ + (T_{DIFS} - T_{SIFS}) \times E_{RX} \end{aligned} \tag{16}$$

Finally, energy consumption has a third component, which is the consumption when there is a medium transmission, but the station is listening to the transmission, not transmitting. We assume here that stations listen to all frames without turning off the radio for the duration of the NAV.

$$\begin{aligned} E_t^{(m)} = (T_{RTS} + T_{CTS} + T_{preamble} + \frac{L}{R^{(m)}} + T_{ACK}) \times E_{RX} \\ + (T_{DIFS} + 3T_{SIFS} + 4T_\rho) \times E_{idle} \end{aligned} \tag{17}$$

5.2 The Energy x Latency Trade-off

In this section we evaluate the energy-latency trade-off using the analytical model proposed above. This evaluation corroborates the fact that using the higher transmission power and modulation tends to perform better than other configurations (e.g. reducing the transmission power to minimize energy consumption). We use equations 1 and 2 to show the results below. We defined four routing strategies, which differ by the reception range of each packet forward, defined by the transmission power and the employed data rate, as shown below.

$$H^{MaxPowerMaxRate} = H^{(P_{max}, 54Mbps)}$$
$$H^{MaxPowerMinRate} = H^{(P_{max}, 6Mbps)}$$
$$H^{MinPowerMaxRate} = H^{(P_{min}, 54Mbps)}$$
$$H^{MinPowerMinRate} = H^{(P_{min}, 6Mbps)}$$

Thus, the configuration $H^{MaxPowerMaxRate}$ represents the configuration used in our routing ameliorations. Next, the configurations $H^{MinPowerMaxRate}$ and $H^{MinPowerMinRate}$ represent the alternatives where nodes first minimize energy consumption, calculated as the amount of energy spent by transmitting one packet (this is the a quite common strategy in MANET routing [3]). Finally, $H^{MaxPowerMinRate}$ was added since the use of a high transmission power greatly reduces the number of possible data forwarders within the stations blocked by a data transmission, that is, the reception range is much lower than the carrier sense range (see Table 2 for values of a real radio). Thus, this last configuration was added to measure the benefit of a larger reception range when compared to the carrier sense range.

We consider that nodes are static and there is no control overhead. The figures below present the results for this model, using the same radio presented in Section 6. Node density was assumed to be 0.1 nodes per square meter, the packet size was set to 1500 bytes, and the distance between the sender and receiver was set to 6 km. We chose this distance in order to have a significant number of hops (6 up to 17 hops, depending on the routing strategy used).

Figures 4 and 5 show the average energy consumption and average latency for varying transmission probabilities per slot, in a network using IEEE 802.11a radios. The curves indicate that it is always best to use a higher transmission power than a smaller one. The results of the analytical model agree with those of the simulations, since they show that higher transmission powers consume less energy and have a lower latency than lower transmission powers. This result diverges from that of Ammari and Das [4], where the authors showed that, in sensor networks, a higher transmission power would incur in less latency and higher energy consumption than small transmission powers, producing an energy-latency trade-off. Our analytical model, however, does not show this trade-off. We attribute this to the simplifications of their model, which did not model medium contention. Another cause for this divergence is that, unlike sensor networks, where the energy consumed by the radio can vary by up to 50% [10], in 802.11 the energy consumed using different transmission powers varies by up to 1%.

6 Simulation Setup

This section presents the configuration of the simulated nodes as well as the parameters of the scenarios. We simulate an IEEE 802.11a network over NS-2 version 2.33. We used the new MAC and PHY models developed in [8], which are more complete than the traditional NS model, once it models

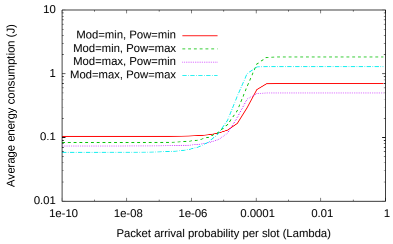

Figura 4: Calculated energy consumption for varying packet arrival rates on a IEEE 802.11a radio.

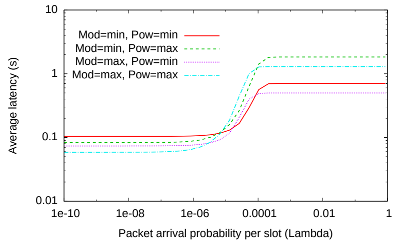

Figura 5: Calculated latency for varying packet arrival rates on a IEEE 802.11a radio.

packet capture during preamble and payload transfers, it supports additive gaussian interference. Finally, this implementation decouples the reception of the preamble and payload, making it possible to receive the preamble but not to receive the payload, as in real networks. It also supports multiple modulation schemes. Packets are received only if the SINR is higher than the ratio defined for each of the supported modulations.

Energy consumption: The original module did not calculate the energy consumed, since it was not within the aims of the authors. Thus, we implemented ourselves the support for energy consumption. Nodes have a different energy consumption for idle, reception and transmission modes, and the consumption for the transmission varies with the transmission power. We do not simulate the switching times from one mode to another.

PER-based packet reception: Using the maximum SINR, the packet size and the modulation scheme we approximate the probability of the correct reception of each frame (the Packet Error Rate – PER) based on traces of real nodes from [28]. Thus, longer frames will have a smaller probability of being correctly received due to errors. The same happens with packets received with a low SINR.

Ricean propagation model: The Ricean model considers slow fading, that is, signal variations due to mobility of objects around the sender and receiver. We use the implementation of the Ricean model described in [24], once it provides a temporal correlation of the fading signal, while others are memory-less. We did not simulate fast fading (due to the mobility of the sender and receiver) because of the lack of temporal correlation on existing implementations, which is very important to the stability of the modulation and transmission power adaptation algorithms. Without this correlation, we would have a severe performance degradation due to unrealistic signal variations.

Automatic rate adaptation: We modified the MAC layer to support automatic rate adaptation. We implemented the following algorithms: AARF [20], RBAR [15], AARFP, RBARP. AARF and RBAR are classic protocols, while AARFP and RBARP are simple extensions for the support of multiple transmission powers. AARFP and RBARP thus attempt to minimize energy consumption by using smaller transmission powers, without penalizing the throughput on the wireless links. Thus, the transmission power is always at the maximum if the modulation used does not provide the maximum throughput, and the transmission power is reduced only if the link can use the modulation with the highest throughput. As an example, if we have a link using 48 Mbps on a 802.11a network, we will try to increase the transmission power to achieve 54Mbps. Meanwhile, if we can attain 54Mbps, then we will try to decrease the transmission power to save energy and reduce contention.

TPC-aware protocols: We use the original implementation of the TPC-aware protocols proposed by Kawadia and Kumar [18], together with our own implementation of CONSET [6][4].

The power consumption and reception thresholds are based on a Cisco 802.11 a/b/g CardBus Wireless LAN card operating on 802.11a mode [9]. For the transmission of packets, we assume the energy consumption model of [14], where the energy consumed at packet transmissions can be broken down into the output signal power of the radio and the consumption of the electronics. The consumption of the electronics is constant, and was derived from the energy consumption figures at the data-sheet of the radio. Preamble and payload capture were activated, thus if an incoming frame arrives at a power that is higher than the one of the current frame, the radio will start to receive the new frame and discard the other, in order to try to recover from what would be a collision (see [8] for more details). The SINR for each of the modulation of a 802.11a radio were based on the values found in [19][5]. For the propagation model, we used a Ricean model to simulate slow fading, where K, which defines the amount of variability of the fading process, is equal to $13dB$. The characteristics of the simulated radio are summarized in Table 2. For all simulations, results are averaged over 60 independent simulations with a confidence interval of 99%.

Parameter	**Value**
SINR for BPSK 1/2 (6 Mbps)	6.02 dB
SINR for BPSK 3/4 (9 Mbps)	7.78 dB
SINR for QPSK 1/2 (12 Mbps)	9.03 dB
SINR for QPSK 3/4 (18 Mbps)	10.79 dB
SINR for QAM16 1/2 (24 Mbps)	17.04 dB
SINR for QAM16 3/4 (36 Mbps)	18.80 dB
SINR for QAM64 2/3 (48 Mbps)	24.05 dB
SINR for QAM64 3/4 (54 Mbps)	24.56 dB
Average medium noise	-99 dBm
Carrier sense threshold	-96 dBm
Preamble capture ratio	2.5118 dB
Payload capture ratio	2.5118 dB
Idle consumption	0.6699W
Reception Consumption	1.049W
Consumption of the electronics	1.6787W
Propagation model	Ricean, K = 13 dB
Transmission Output Strength	$[0.01, 0.013, 0.02, 0.025, 0.04]$ W

Tabela 2: PHY parameters of the simulated radio.

6.1 Validation of the implemented code

Due to the amount of code that had to be implemented and integrated in order to make the simulations more realistic, in this section we briefly describe one of the sanity tests that we performed to check the simulator. This scenario consists of two nodes, transmitting UDP frames whenever possible, in order to measure the maximum throughput of the network. This simple scenario exercises the automatic rate adaptation protocols, the energy consumption code as well as the PER implementation. The default transmission power was the third one in Table 2, so we could exercise the TPC aspect of the TPC-aware adaptation strategies. In order to provide a fair comparison of the data rate adaptation protocols, we activated medium reservation for all the protocols. We also provide results for the optimal configuration, which is chosen as the modulation scheme that achieves the highest data rate when no rate adaptation scheme is employed.

Figure 6 shows the throughput of the eight modulation schemes of 802.11a when no rate adaptation is employed. This Figure shows that each modula-

[4]Those protocols are explained in the related work section.

[5]Those thresholds depend mostly on the frequency and the characteristics of each modulation, thus they do not change much from one radio to the other

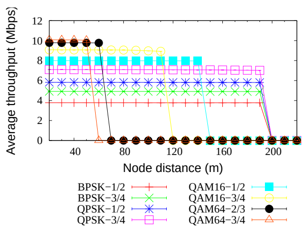

Figura 6: One-hop throughput without RA.

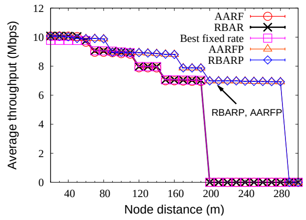

Figura 7: One-hop throughput with RA.

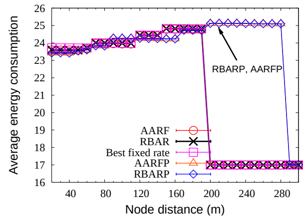

Figura 8: Energy consumption on links using RA.

tion can be used up to a certain distance, when the SINR allows the correct reception of frames. Further, modulations with higher data rates have a smaller range, since they require higher SINRs to operate. Hence, the ideal scenario for a TPC algorithm would be to follow the best results of all the curves, changing from a modulation with higher throughput to other with lower throughput when the former does not allow the correct reception of frames.

Figure 7 shows the throughput for different node distances with the implemented rate adaptation and transmission power algorithms. The results are consistent with other articles in the literature, forming a decreasing step-shaped function. This represents the use of different data rates, which change according to the SINR at the receiver. Note that the measured throughput is not the same as the nominal throughput of the link, due to the overhead of medium reservation, acknowledgement and waiting times. The AARFP and RBARP protocols transmitted frames at higher data rates for farther distances than the other protocols, due to their use of TPC. Thus, when those protocols detected that the transmission power was not enough to allow the reception of the packet, they would resort to higher transmission powers.

Another interesting result is that there are not eight steps, as one would expect. When we look at the data rate for each of the plateaus, we see that some of the levels were skipped, and the skipped levels were usually the ones where the same modulation strategy was used, however the bit/baud ratio changed (e.g. QAM-64 2/3 and QAM-64 3/4). This occurred because their reception thresholds are quite similar, as we can see in Table 2. We believe, however, that if we were to simulate distances with a smaller grain, we would find the eight different plateaus. This can also be due to the value of the carrier sense threshold, which may be set too high. Since we cannot lower the transmission power below the carrier sense threshold, it may occur that in networks with no interference and a high carrier sense threshold, the SINR ratio will be always high, allowing the use of more spectrum efficient modulations. Other interesting effect seen on this graph is that the TPC-aware strategies could attain higher throughput for more time, since they increased the transmission power when the modulation was about to change.

Figure 8 shows the energy consumption. Note that the energy consumed increases when the throughput of the link decreases. The energy curve shows that modulations with a higher data rate will consume less energy on the link. This is quite simple to show why: For a 512 bytes packet, when using RTS/CTS, the RTS will reserve the medium during 244 microseconds for 54Mbps, and for 912 microseconds for 6Mbps. The time required to transmit the data frame for the first case is 104 μsec, while for the second it takes 772 μsec. Thus, when we subtract the two SIFS intervals that radios stay in idle mode, we see that the radio will be in reception mode for 108 μsec, waiting for the ACK and the CTS. When we divide the reservation time by the time in reception mode, which consume less energy, we see that for 54Mbps the radio will be 44% of the time in reception mode, while for 6Mbps it will be only 11% of the time. Hence, this is the reason for the slight increase in energy consumption.

Since the energy consumed when changing the transmission power is quite subtle, varying a few percents from the maximum to the minimum power, this Figure does not show easily the different energy consumption when changing the transmission power. However, when analyzing the individual values we saw that the energy consumed increased with the distance for scenarios where the link rate was 54Mbps. This shows that, on this situation, the TPC-aware protocols reduced the energy. Meanwhile, for other link speeds, those strategies optimized the data rate at the detriment of energy consumption, thus they always employed the maximum transmission power.

7 Results

This section presents the results for the comparison of our TPC- and RA-aware extensions over DSDV, which we will refer to from now on as DSDV-TPCA. We compare DSDV-TPCA against ClusterPOW, CONSET running over DSDV and an unmodified version of DSDV. Since ClusterPOW also uses DSDV internally, we can evaluate more easily the effects of the TPC and RA on the routing decisions.

In the simulated scenario, fifty nodes are placed on a rectangular region, where the height is always half of the width (e.g. 2 km x 1 km, 4 km x 2 km), in order to increase hop counts. Forty-four nodes are randomly placed and mobile, while six nodes (the sender and receivers of three data flows) are fixed and static. This configuration allows us to increase the contention when

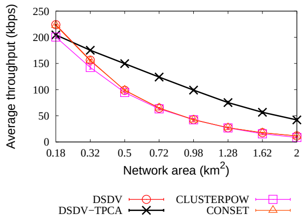

Figura 9: Average throughput.

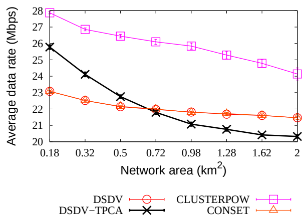

Figura 10: Average data rate of a path.

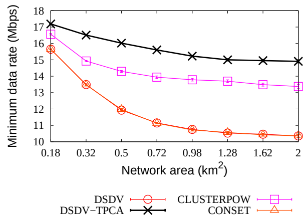

Figura 11: Minimum data rate of a path.

the size of the area decreases, and enlarge the distance among nodes when the size of the area is increased. The evaluated scenario models a multimedia application, in which users transmit video streams. There are three flows in the network, all of them based on real video traces of video streams encoded with H.263 at 256kbps [11]. Nodes move following the random way-point mobility model, with an average speed of 2m/s. In order to maximize the number of hops traversed by each packet, the senders and receivers are in opposite corners. The simulations last 400s, allowing all flows to reach by far a stationary state. All protocol parameters were empirically tuned to this scenario.

The average throughput of the flows is shown in Figure 9. DSDV-TPCA performs the best, due to its reduced control overhead, as well as to the use of higher data rate routes. DSDV-TPCA achieved an improvement of up to 50kbps over the other protocols, showing the benefits of its routing decisions. Figure 10 shows the average data rate. ClusterPOW achieved the best performance. This is because using more hops, in general, leads to links with higher data rates, since intermediary nodes will be closer to one another. Although ClusterPOW presented a high data rate, its throughput was quite similar to that of DSDV and CONSET, due to its high routing overhead. Since ClusterPOW does not take the modulation into account in its routing decisions, the minimum data rate of the path may be smaller than that of DSDV-TPCA, as shown in Figure 11. Hence, since the minimum data rate determines the throughput of the path, DSDV-TPCA still has a better performance.

Even though CONSET builds low energy routes, its choices were quite similar to DSDV's, once CONSET considers the final energy consumption, not the transmission power, to define its neighborhood. CONSET reduces the neighborhood of a node in the following way: if a certain neighbor node N_1 can be reached via another neighbor (e.g. N_2) with a energy consumption lower than the direct route, then N_1 is removed from the neighbor list. Once the highest transmission power consumes only 1 to 2% more than the lowest one (values derived from Table 2), CONSET will rarely reduce its neighborhood, and thus it operates similarly to DSDV.

Regarding energy consumption, shown in Figure 12, DSDV-TPCA consumed less energy than the other protocols for dense networks, while for scenarios with a lower density (a network area of more than 0.98 km^2) all protocols performed similarly. This happened mostly due to the cost of building routes, which is almost the same for all protocols in networks of more than 1.28 km^2. ClusterPOW came in second, since it tries to reduce the transmission power, and hence the amount of contention on the network. CONSET was the third less energy consuming protocol, since it reduces the transmission power only when link energy consumption will be reduced. The comparison of ClusterPOW and CONSET shows the benefits of decreasing the transmission power to reduce contention. As we saw in the analytical model shown in Section 5.2, the number of retransmissions on the link has a significant impact on the end-to-end energy consumption and latency.

Finally, Figures 13 and 14 present results for average latency and jitter, respectively. Those two metrics are quite important in the transport of multimedia traffic. Average latency determines when the user may start the playback of the media and the interactivity of a two-way communication, while jitter determines sound and image quality (once it is the responsible for skips due to frames received after their deadline). Both ClusterPOW and DSDV-TPCA performed the best, reducing average latency and jitter by at least one order of magnitude when compared to DSDV and to CONSET. DSDV-TPCA performed a bit worse than ClusterPOW for larger areas. We believe that this is due to the higher throughput of DSDV-TPCA, which introduces more delays since there could be more packets in the queues of each intermediary node.

A very important source of delays in routing is route breaks, once packets queue up at the extremities of the “broken” link up to the moment when a new route is established. The use of modulation and transmission power adaptation algorithms running at the MAC layer makes the task of detecting broken routes much harder to routing protocols. Take, for example, trial and error adaptation algorithms such as ARF and its derivations [20]. Those protocols send packets from time to time using a more spectrum efficient modulation to test the medium. Those packets are frequently lost, since the link is already operating at its highest achievable modulation. Likewise, fading may cause bursts of packet losses. Although these effects may last at most a few seconds, in both situations routing tends to think that the link is broken, triggering route invalidation processes and sending new route advertisement packets. Those actions increase considerably the delays in the network, as more control packets increase contention for packets already in

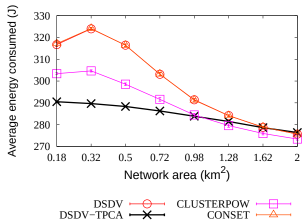

Figura 12: Average energy consumption.

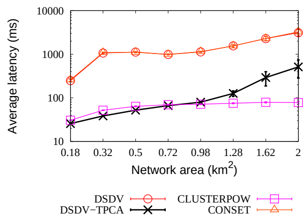

Figura 13: Average latency.

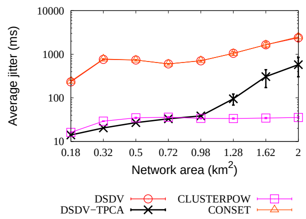

Figura 14: Average jitter.

route, while queued packets have to wait for the establishment of a new route. Thus, more research is required in the interaction of the lower layers with the routing layer in order to identify the exact cause of packet losses, which may then be used to improve routing decisions.

8 Conclusions

In mobile ad hoc networks (MANETs), radio transmissions may have different powers and may use different modulation schemes. These two characteristics affect medium contention, packet delay, network throughput and energy consumption. Thus, it is in the best interest of a network to dynamically adjust both parameters in order to maximize its performance. Several MAC and PHY level protocols have been proposed in the recent years, but no existing routing protocol considers both the transmission power and modulation to build their routes. Routing must be aware of both, once ignoring transmission power and modulation may lead to the creation of paths that consume too much energy or provide low throughput.

This work has presented generic modifications to the MAC and routing layers of MANETs that build energy, transmission power and data rate aware routes. First, MAC-level broadcast packets assess the transmission power and modulation of wireless links in a scalable way. Next, adaptations to the routing minimization function allow the establishment of routes that take link conditions into account. The proposed modifications are quite simple and generic and thus are applicable to a wide range of networks. Those modifications prioritize smaller hop counts, instead of the common assumption of using higher hop counts. This decision is justified by an analytical model of multi-hop MANETs that indicates that routes with less hops reduce energy consumption and end-to-end latency. Simulations showed that our modifications reduced latency by up to one order of magnitude, while throughput has increased by up to 30%.

This research can be continued to explore more dynamic scenarios, for example radio models with fast fading such as Nakagami and scenarios with higher node mobility. We also plan to investigate ways to increase the cooperation among layers in order to reduce the number of unnecessary route reconstructions.

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