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Abstract— **Due to energy constraints on mobile ad hoc networks (MANETs), networking protocols try to reduce energy consumption on the communication. Transmission power control (TPC) is one such technique, where nodes transmit frames at the minimum power necessary to reach the destination. Several studies evaluated the effects of TPC on MANETs, however their modeling of the physical and MAC layers usually does not correspond to the characteristics of real hardware. Important factors, such as collisions, the limited number of transmission powers, the capture effect and the dynamic selection of modulation and coding have not been taken into account. This article presents a comprehensive evaluation of TPC techniques considering the factors above to provide more realistic radio models. Results show that certain hardware and medium characteristics can be ignored, while the existence of a finite number of transmission levels must be considered in the model. We confirm the existence of a energy-latency trade-off on sensor networks, however we refute this trade-off on TPC-aware MANETs. Finally, we show that TPC-aware routing protocols for MANETs should minimize hop count instead of energy consumption, as opposed to existing TPC protocols.**

I. Introduction

Mobile devices are frequently used in situations where 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), acting as source and data sinks, but also as data forwarders [1]. Since the devices operate on batteries, communication protocols minimize the amount and size of the packets to reduce energy consumption and consequently increase the lifespan of the devices. Another energy-saving mechanism is the adjustment of 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 [2].

Transmission Power Control (TPC) protocols have been studied in two different networking levels. Several works [2]–[6] 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 be considered on a network level, as the routes must be composed of energy-efficient links. Analytical studies showed the impact of TPC on a network level [7], [8], while others proposed TPC-aware routing algorithms [9]–[11]. However, our previous work on MAC-level TPC protocols [6] showed that several of the assumptions made on other works are too simplistic. For example, most studies do not take into account the existence of the capture effect and the dynamic changing of modulation and coding on the PHY layer.

Further, the creation of TPC-aware routing is not simple, since several parameters must be taken into account. The transmission power determines the data rate of the link, the amount of collisions on the network and the latency of the packets. Moreover, those parameters are orthogonal, as a higher data rate will demand a higher transmission power, which in turn will increase the energy consumed.

The article has two contributions. First, it is a comprehensive study of the impacts of transmission power on the network as a whole, taking into account several parameters of the radio. We start using a simple model, incrementing it with features one at a time and measuring their impact individually. This strategy allows us to identify which radio characteristics are important on the evaluation of TPC techniques and what is their influence on the simulation results. Second, we re-evaluate some performance assumptions and design decisions made on previous work over a more complete radio model, showing that some of them do not seem to be valid on more realistic scenarios. Such an extensive evaluation is necessary to characterize the behavior of TPC techniques, in order to provide a solid base upon which other researchers may develop efficient TPC-aware solutions for MANETs.

The rest of the paper is organized as follows. Section II presents the related work. Section III describes important details of wireless communications which are usually ignored on TPC studies. Section IV describes the simulation setup. Next, Section V details our findings and analyzes the performance of TPC-aware networks. Finally, Section VI presents the conclusions and future work.

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II. Related Work

The problem of transmission power control has been extensively studied on the point of view of MAC protocols, where techniques have been proposed to identify the minimum transmission power for a link [2]–[6], [12]. The techniques are either iterative, where the transmission power is dynamically adjusted to keep a constant link quality [6], or instantaneous, where calculations are employed to identify the ideal transmission power at each individual packet [2]–[6], [12]. Being MAC-layer solutions, their performance evaluation is limited to a single hop and focuses only on energy consumption, leaving important issues such as the end-to-end latency and throughput. Meanwhile, this article evaluates the effect of TPC techniques on the entire network.

A problem related to transmission power control is the propagation of wireless signals. Lal et al. showed that the reliability of a link varies greatly and proposed algorithms to assess link reliability [13]. Reijers et al. studied the effect of obstacles and environmental changes on link quality [14]. Zhou et al. developed a propagation model that closely resembles the results obtained from experimental data [15]. Son et al. studied concurrent transmissions on low-power radios, showing that collisions occur only when the reception strength of the signals vary by a few dBms [16]. This is due to the capture effect. Whitehouse et al. used the capture effect to significantly reduce collisions, by allowing nodes to listen to preambles during incoming data transfers [17]. Thus, the receiver always decodes the stronger signal, instead of failing to receive both frames.

De Couto et al. proposed an extension to DSR, where the routing algorithm takes into account the reliability of the links, greatly reducing the amount of retransmissions [18]. In our view, TPC techniques significantly reduce the amount of bad links, as nodes will increase the transmission power to minimize packet losses. Lin et al. observed that TPC-aware MAC protocols seem to improve packet reception rates over traditional MAC protocols [12]. However, a more extensive study must be carried out in order to characterize the reliability of links on TPC-aware networks.

The benefits of TPC on multi-hop wireless networks have been analytically studied by Gomez and Campbell [7]. They showed that per-link range adjustments outperform global range transmission adjustments by 50%. Thus, instead of globally defining a transmission range that keeps the network connected, wireless networks should adjust the transmission range on each link. Further, the average per node traffic capacity is constant even if more nodes are added to the network when TPC is used. Meanwhile, for networks employing fixed transmission power, the capacity decreases as more nodes are added. Their study, however, does not consider that real transceivers have a limited set of available transmission powers, and the capture effect was also not taken into account.

Ammari and Das analytically evaluated the effects of TPC on latency and energy consumption on WSNs [8]. By increasing the distance traveled at each hop, the overall latency decreases at the cost of a higher energy consumption. For a small distance per hop, however, less energy is consumed, but the latency increases as more hops must be traversed. Thus, the authors proposed quality of service (QoS) classes with different latency and energy guarantees based on the transmission power employed on the communication. The authors assumed several simplifications on the MAC layer. They did not consider the effects of collisions on the communication, which become critical as the transmission power increases. They also assume that radios can tune the transmission power to any value. Finally, they do not deal with collisions and the capture effect, which would affect the calculation of the delay. This work, on the other hand, re-evaluates the proposed energy-latency trade-off using a more realistic radio and physical layer model.

Despite being an issue that concerns both routing and MAC layers, the CONSET protocol presents a MAC-level solution to TPC-aware routing [9]. 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, routes will be energy-efficient, 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 and coding, which is a mandatory characteristic of the standard, as we explain in the next section.

Kawadia and Kumar proposed four TPC-aware routing protocols that minimize the energy consumption on MANETs [10]. Those protocols execute several instances of a routing algorithm, one for each transmission power available. Data are sent through the route which employs the least transmission power. While the results take into account collisions, a limited set of transmission powers and the capture effect, this strategy demands a high amount of energy due to the several instances of the routing algorithm. Further, their radio model does not take into account the dynamic fluctuation of modulation and coding. Since the authors' aim is to demonstrate that their protocol outperforms the traditional ones, they do not attempt to characterize the performance of TPC-aware protocols as a whole, as this article proposes.

III. Background

This section presents an overview of phenomena in wireless communications, such as packet capture, the dynamic per-link adjustment of modulation and coding and the energy-latency trade-off. They are important in the design of TPC-aware protocols for wireless networks, and sometimes are overlooked on simulation and analytical studies.

A. Packet Capture

One important phenomenon in wireless communications is the capture effect, which occurs when two stations send packets at the same time [17]. In wireless channels with capture, the simultaneous transmission of two or more signals does not always incurs on a collision. If one of the signals arrives at a much higher strength than the others, the receiver correctly decodes the stronger signal, while ignoring the remaining transmissions.

Suppose, for example, that capture occurs for a signal difference of 5 dBm. Thus, when a node receives two concurrent transmissions at reception powers of -80 and -70 dBm, the transmission at -70 dBm will be correctly received while the other will be ignored, that is, the receiver *captures* the signal with higher power. Further, for this case, a collision would only occur if the reception strength of the second signal was higher than -75 dBm.

Due to the capture effect, the number of collisions is reduced. This reduction depends on the signal strength required for a packet to capture other concurrent packets, and is called *capture threshold*. Small capture thresholds should mitigate more collisions, as the frequency of packets captured should increase. Conversely, higher capture thresholds will mean more collisions, as the signal from multiple transmissions will not be discernible most of the time.

B. Adaptive Modulation and Coding

Nowadays, most wireless standards (e.g WiFi and WiMax) perform some sort of dynamic adaptation of modulation and coding (AMC) [19]. This technique copes with interference and bad links, and works as follows. Wireless cards actively sense the quality of the link. If the reception is good and the signal arrives at a high power on the receiver, then the sender codes the data using efficient modulation and coding schemes. However, if the signal quality is not good due to interference or due to a weak signal at the receiver, the sender uses modulation and coding schemes that are more resilient. Resiliency, in this case, implies in a lower data rate.

AMC is well-known to users of structured WiFi networks. Stations near the AP will most likely transmit at higher bandwidths (e.g. 54Mbps on 802.11g), while distant ones will transmit at 6Mbps, for example. This change is possible because modulation/coding pairs with lower data rates require a lower reception strength, called *reception threshold*, to be correctly decoded (As an example, see Table I for the thresholds of a real radio). As a consequence, frames transmitted using lower data rates will have a larger range, as illustrated in Table II.

The WiFi and WiMax standards define a finite set of modulation/coding pairs, which must be supported by all compliant cards. On IEEE 802.11b, those vary from 1Mbps up to 11Mbps, while on 802.11g those vary from 6Mbps up to 54Mbps, when the network is composed of only 802.11g stations, and from 1Mbps up to 54Mbps on networks with stations using both standards. Wireless standards that use AMC do not specify the algorithm that dynamically selects the best modulation and coding pair for each link, thus each vendor employs its own solution, which is usually proprietary.

Besides varying the data rate, AMC influences the occupation of the medium, as frames transmitted at a lower data rate will demand longer transmission times. As an example, the transfer of a 11MB file using a 11Mbps link would take approximately the same time of transferring a 1MB file on a 1Mbps link. AMC also impacts TPC protocols, as each modulation/coding pair has a different minimum reception power, which increases with the data rate obtained. Thus, in order to achieve higher data rates, TPC protocols must employ higher transmission powers. Further, those levels might differ for each manufacturer or card, and thus should not be hard-coded on the TPC algorithms. AMC must be considered in routing, since it may define the throughput of the flows. Figure 1 shows an example where a routing protocol chooses the smallest hop route, illustrated by the yellow wireless links. This route will support up to 2Mbps, since this is the speed of the slowest link. Even though the sender could transmit at 11Mbps to the first hop, packets would accumulate there, since the last link on the path is limited to 2Mbps. Thus, the routing algorithm should choose the longest path, marked in red, in order to increase the maximum throughput to 5.5Mbps.

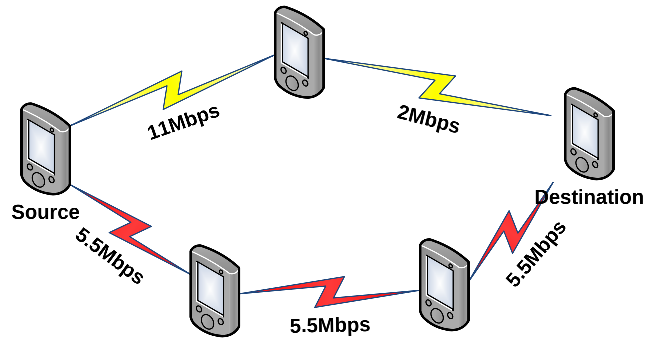

Fig. 1. The effect of adaptive modulation and coding in routing.

Another method to cope with interference is the dynamic selection of channels, used in UWB (Ultra Wide Band) and PLC (Power Line Communications) networks. On such networks, links are composed of several channels, and only the channels which have an acceptable amount of interference are used. We do not model multiple channels in this work.

C. The Energy-Latency Trade-Off

Ammari and Das suggested in [8] that the energy consumption and latency of a packet could be changed by carefully adjusting its transmission power on each hop of its path, as illustrated in Figure 2. If routes use a reduced transmission power, shown in the top box, packets will have to traverse a large number of hops, hence latency would be higher than that of a route produced using higher transmission powers (bottom box). However, the energy consumed would be smaller on longer routes, since the transmission power required to reach a given node is usually proportional to the square of the distance. Thus, protocols would have the choice to use a high transmission power to reduce latency at the cost of energy consumption, or they could use a lower transmission power to prioritize energy consumption.

The average transmission power used per hop may be used to either prioritize energy consumption or latency, creating an *energy-latency trade-off*. Furthermore, we could define different forwarding classes, with different expected energy

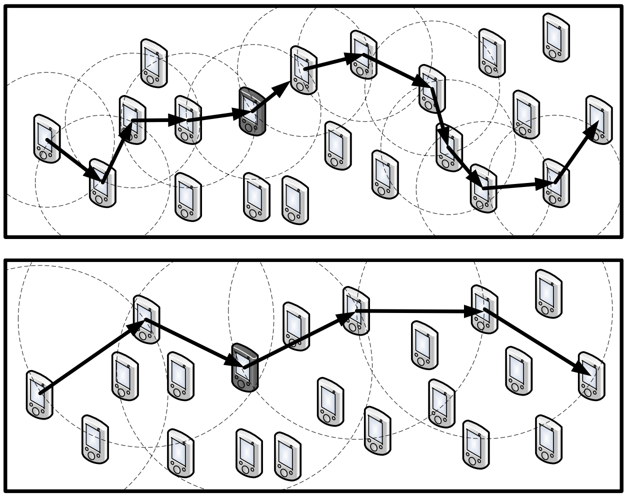

Fig. 2. The energy-latency trade-off in MANETs.

consumption and delay. Prioritary packets could be sent using smaller routes, reducing their delay at the expense of a higher energy consumption, while ordinary packets would traverse longer routes in order to save energy.

As mentioned previously, Ammari and Das employed simple analytical models to demonstrate the energy-latency trade-off, ignoring the effect of collisions. Since a higher transmission power also increases the likelihood of collisions, we believe that the use of higher transmission powers may not always reduce the latency of a packet. As an example, the grey node in Figure 2 will interfere with the transmissions of only two nodes if it uses the small transmission power (top box). However, if it increases the transmission power, it may interfere with nine nodes (bottom box). Thus, we evaluate the energy-latency trade-off on a more realistic model, which considers collisions.

IV. Evaluation Setup

The evaluation was performed on the NS-2 simulator version 2.29.3 [20]. We used the extensions implemented by Kawadia and Kumar [10] over the IEEE 802.11 protocol. The simulations were comprised of three main parts. The network model, which comprises the routing, MAC and PHY phenomena and protocols; the application characterization, which describing the application flows, location, mobility and amount of nodes employed; and the evaluated metrics. We describe those below.

A. Network Model

The PHY model employed is the standard NS implementation, enhanced with AMC and dynamic transmission power adjustment. The simulations employ the Two Ray Ground propagation model, since our study focus on the impact of TPC on the network layer. We are interested, thus, on the amount of contention and latency caused by TPC. A more realistic model, in this case, would only complicate the analysis of the results due to more frequent changes in the transmission power, in order to compensate fluctuations on the noise and on the propagation characteristics of the environment. Thus, our propagation model assumes that the signal propagates evenly on all directions, and that the level of interference in the medium is constant.

All MAC and PHY parameters are based on a Cisco 802.11 a/b/g CardBus adapter operating in 802.11b mode [21]. The carrier sense sensitivity and the capture threshold were set to -88 dBm and 10 dBm, respectively. Each modulation/coding pair has a different reception threshold, which is the minimum signal strength necessary to correctly decode the incoming signal. The values were taken from the specifications provided by Cisco, and are summarized in Table I.

Data rate	Rx. Threshold
11Mbps	-85 dBm
5.5Mbps	-89 dBm
2Mbps	-91 dBm
1Mbps	-94 dBm

TABLE I

Reception thresholds for the simulated radio.

The transmission powers and their respective consumption, shown in Table II. The transmission powers are named, since we will refer to them individually in the scenario V-D. We assume that the transmission power is the sum of the energy spent by the electronics and the energy spent transmitting data. The consumption of the electronics is assumed to be 1678.7mW for every transmission power, and was based on the energy consumed on the maximum transmit power informed on the data-sheet minus the output power of the signal. The energy on idle and reception modes for this card are 669.9 mW and 1079.1 mW, respectively.

In order to evaluate the effect of each component of wireless communication separately, we start our simulations with simple radio model, increasing its complexity on each scenario. The simplest model does not consider the effect of capture, the radio can arbitrarily set the transmission power to any desired value and there is no dynamic change of modulation and coding (AMC). Further, for every setup without AMC, we employ the reception thresholds and maximum range of links operating at the maximum data rate, 11Mbps.

Concerning routing, we adopted the Dijkstra algorithm for minimum paths in graphs. Note that there might be multiple edges linking the same pair of nodes, one for each combination of modulation, coding and transmission power where the correct reception of the packet is possible, that is, the reception power is above the reception threshold for the given modulation and coding employed to transmit the packet. The edges have two important characteristics that can be considered in routing, which are the data rate and the energy consumption. By employing, one, two or none of those characteristics on Dijkstra's minimization function, we may build routes differently. This work uses three strategies. The first one, which we call *ME* (minimum energy), minimizes only energy consumption. In the second function, called *MH*

Name	Tx. Power	Power Consumption	Transmission Range (m)			
			1Mbps	2Mbps	5.5Mbps	11Mbps
P_{TX} 1	10 dBm	1688.7 mW	597m	502m	447m	355m
P_{TX} 2	13 dBm	1698.7 mW	710m	597m	532m	423m
P_{TX} 3	15 dBm	1708.7 mW	785m	661m	589m	468m
P_{TX} 4	17 dBm	1728.7 mW	892m	751m	669m	532m
P_{TX} 5	18 dBm	1743.7 mW	946m	796m	709m	563m
P_{TX} 6	20 dBm	1778.7 mW	1061m	893m	796m	632m

TABLE II

TRANSMISSION POWERS AND RANGES FOR THE SIMULATED RADIO.

(minimum hop), the function minimizes hop count and next energy consumption, giving priority to smaller paths. The last function, called *MHA* (Minimum Hop with AMC). first tries to maximize the data rate, next minimize the number of hops and next the energy consumed.

All scenarios, except scenarios V-E and V-D, use the ME minimization function, which is the "classic" operation of TPC-aware routing propositions. Scenarios V-E and V-D, on the other hand, explore different aspects of TPC-aware routing, thus requiring the other two protocols.

The quality of the routes depends on the frequency of routing updates and on the time taken for routes to converge. Since our focus is not on routing algorithms, but on the effects of TPC on routing and MAC, we suppress route propagation messages on all protocols. Thus, routes are built based on the omniscient knowledge of nodes' location, allowing us to calculate the data rate, energy and reachability of all nodes.

B. Application Characterization

The evaluated scenarios consist of static networks, where nodes send data on UDP streams. We chose UDP instead of TCP since the lack of congestion control simplifies the analysis of the results. To maximize hop count, the sender and the receiver of each flow are placed on the corners of the region, where senders are on the opposite corner of the receivers, e.g, the node on the top left corner transmits to the node on the bottom right corner. All other nodes are randomly placed using a uniform distribution.

We performed simulations for three traffic types. The first, which we call *heavy*, was based on the streaming of videos encoded with the H.263 codec, at a rate of 256kbps. The second, called *light*, simulates the streaming of the same videos, however encoded at 64kbps. The two types use the traces characterized in [22]. Those traces are based on the encoding of several films, TV series and seminars using the H.263 codec. Both heavy and light scenarios employ four multimedia flows. We chose to stream films because they have the biggest variation in frame sizes, thus being the most demanding type of video. For reference, our simulations use the traces based on the films *Jurassic Park*, *Silence of the lambs*, *Star Wars VI* and *Robin Hood*. The third traffic type models bursty traffic, based on VoIP calls encoded in PCM. Four nodes transmit data at a constant data rate of 64kbps, using an on/off traffic source where the burst and off times are exponentially distributed with lambda equal to 1.004s and 1.587s, respectively. Those values are based on the ITU P.59 recommendation for voice modelling [23].

We suppressed RTS/CTS and ARP messages in the MAC layer. All nodes employ the same radio and have an infinite supply of energy. The simulations last for $50s$, enough time for all flows to reach a stationary state. Unless stated otherwise, all scenarios use the parameters described above.

C. Metrics

The evaluation focused on five main metrics, which are directly influenced by the transmission power employed in wireless communication. We describe each one below.

Number of collisions: Indicates the contention on the network, as the number of collisions is associated with the amount of nodes trying to transmit data at the same time. The transmission power will influence the amount of nodes competing against each other, in turn affecting the number of packet collisions.

Number of hops: This metric influences the delay and energy consumption of the network, as more hops will require more packet forwards. More retransmissions will also increase medium contention. The transmission power, together with the routing algorithm, determine how many hops a packet must traverse to reach its destination.

Energy consumption per node: The energy consumed will determine the lifetime of the network, hence protocols should strive to reduce their energy spendings. The energy consumed in the communication is a function of the number of retransmissions on the MAC layer, dictated by the number of hops and packet collisions, and also by the output power of the signal. While a reduced transmission power decreases the consumption related to the latter, it may increase the former.

Packet latency: The latency is determined by the number of hops traversed, the amount of retransmissions required on each hop, and the data rate used on each hop. All of those components are directly influenced by the transmission power.

Average per-link data rate: Contributes to the throughput of the network, packet delay (mentioned on the previous item) and the amount of packet drops. Since a route is composed of multiple links, the maximum throughput will be dictated by the speed of the slowest link on the route. If no flow control algorithm is employed, faster links may overflow slower ones with packets, which must be queued for later forwarding. When the queue is full, packets start to be dropped. This metric is only evaluated in the scenarios with AMC, since on the others all links have the same data rate.

All the results presented in the next section are averaged over 60 independent simulations and plotted with a 99% confidence interval.

V. RESULTS

This section is divided in parts, one for each evaluated parameter or supposition. Section V-A compares a radio model that use discrete power levels against a model using arbitrary power levels. Next, Section V-B evaluates the impact of the capture effect, followed by a study of medium reservation on TPC-aware networks on Section V-C. Section V-D checks if it is possible to trade-off energy consumption and latency by varying the transmission power. Since most wireless standards use AMC, Section V-E shows the impact of AMC on TPC-aware networks.

A. Arbitrary Transmission Power Levels

This scenario compares the use of arbitrary transmission powers against a more realistic radio model on networks with different densities. Two radio models were employed. In the *arbitrary power* model, nodes send packets at the *exact transmission power* required by each hop, similar to the assumptions made on analytical models [7], [8]. In the *discrete power* model, nodes have a limited number of transmission powers to choose from, as Table II shows.

This scenario uses a rectangular area, with dimensions 1km$x$2km, in order to maximize the number of hops travelled. We vary the number of nodes deployed from 50 up to 300 nodes, in order to evaluate if the capacity of the network increases with the number of nodes deployed, as described by Gomez and Campbell [7]. Since the protocols showed the same trends for the three traffic types, we show only the results for the lighter load.

Figure 3 shows the average energy consumption. The consumption for the arbitrary model decreases with more nodes, since paths use more and more nodes, allowing the use of lower transmission powers. Meanwhile, the discrete power model had a constant energy consumption, since nodes could not decrease any further their transmission powers, and thus the average number of hops remained the same. Figure 4 shows the average hop count. The number of hops affected the average latency, which is shown in Figure 5. More hops mean more time for packets to reach their destination. Thus, the arbitrary model doubled the average latency due to the increase of hops. The discrete model, on the other hand, remained stable.

The increase in latency is also due to the number of collisions, which are depicted in Figure 6. The inclination of this curve is much the same of the latency, suggesting that the increased latency is due to a higher number of collisions. Even though there were more collisions, the throughput and the delivery rate suffered minor variations for all traffic types.

The results above show that the arbitrary radio model diverges significantly from the discrete model when varying node density. The number of hops and collisions is much more elevated on the arbitrary model and, as a consequence, the average latency is affected.

B. The Capture Effect

This scenario evaluates how packet capture (described in Section III-A) impacts the performance of TPC-aware networks. We compare a network without capture (capture threshold set to an infinite value) against networks with a capture threshold of 5, 10, 15 and 20 dBm. Two hundred nodes are placed on a 1km$x$2km area. All other parameters are the same of the previous simulation, and we employ the discrete power radio model, as it is more realistic than the arbitrary power model.

Figure 7 shows the average amount of collisions. The number of collisions increases with the capture threshold, up to the moment when there is no capture. When capture occurs, part of the packets that would cause a collision are "absorbed" by the stronger signal. For example, when capture occurs at 5 dBm, the effect suppressed up to 35% of the collisions on the lighter load, 39% on the heavy load, and 44% on the bursty load. Even though the light and bursty load have a similar average output packet rate, the capture effect was more beneficial to the latter. We believe that, since queues are higher on bursty traffic than on CBR traffic, the amount of contention on the medium is slightly higher on bursty loads, thus the packet capture tends to occur more. Further, the bursty traffic itself is composed of much smaller packets, increasing the competition on the medium.

Due to less frequent collisions, latency is smaller on networks where capture exists. Figure 8 shows this behavior. While the amount of packets captured depends mostly on the amount of packets sent, the influence of the capture effect is more significant on higher loads. While the bursty and heavy loads displayed statistically insignificant variations, the heavy load increased its latency by up to 100%.

This scenario shows that the capture effect should not be removed on the simulation of MANETs when heavy loads are considered. However, the simulation of lighter loads seems to be accurate without taking capture into account. Further, we simulate the capture effect on all the subsequent scenarios of this paper, using a threshold of 10dBm. This value was arbitrarily chosen, since we were unable to find any study approximating this threshold on MANETs.

C. Medium Reservation

This scenario evaluates the effect of medium reservation on TPC-aware communications. We repeated the simulations of the former scenario, however this time turning on RTS/CTS dialogue. The number of nodes and area of the region resemble those of Section V-A.

Apart from the average latency, collisions and energy consumption, all the metrics performed similar with or without reservation. The use of medium reservation dramatically reduced the amount of collisions, achieving results from eight up to ten times smaller. This effect was more pronounced on

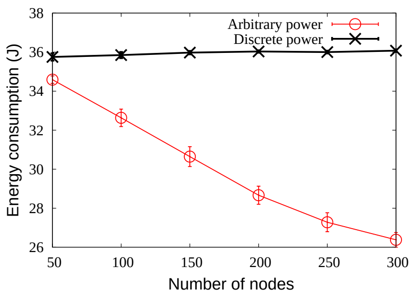

Fig. 3. Average energy consumption.

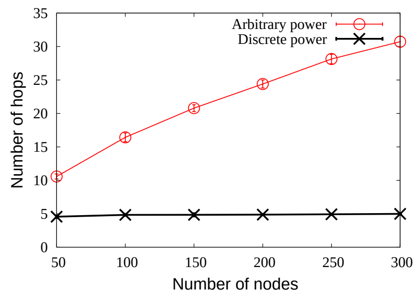

Fig. 4. Average number of hops.

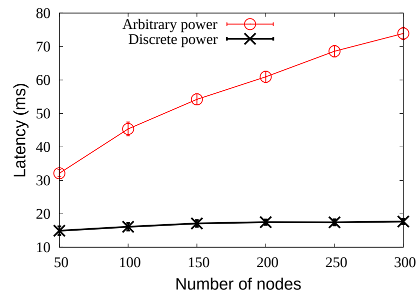

Fig. 5. Average latency.

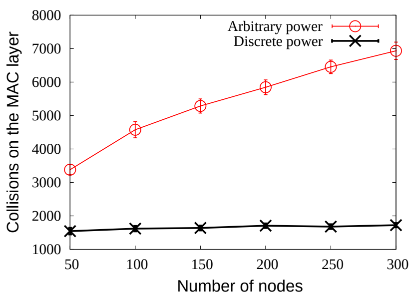

Fig. 6. Average number of collisions.

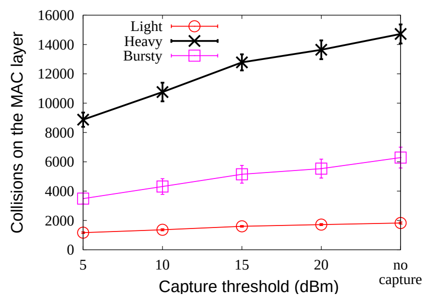

Fig. 7. Average number of collisions.

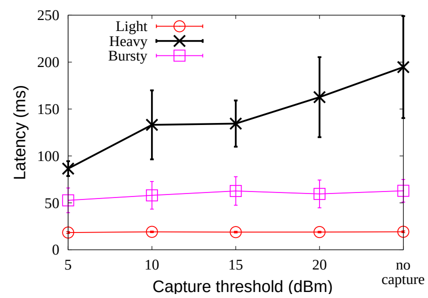

Fig. 8. Average latency.

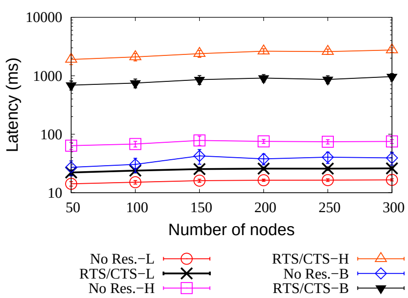

Fig. 9. Average latency.

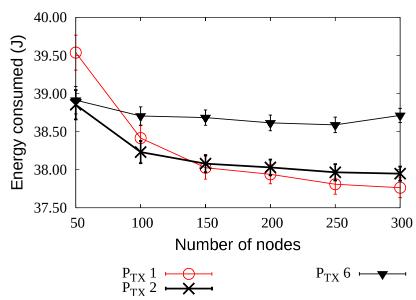

Fig. 10. Average energy consumption.

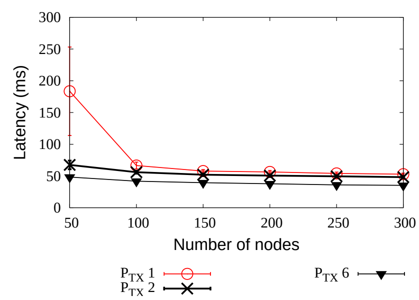

Fig. 11. Average latency.

the bursty traffic, since it was comprised of a high number of packets. However, the amount of energy consumed was 4 to 10% higher using medium reservation techniques. The most surprising result was that the average latency was smaller when medium reservation was not used, as Figure 9 shows (L curves show the light traffic, M the medium traffic and B the bursty traffic). This occurred because there were still as much collisions using medium reservation. However, those occurred on the RTS frames instead on the data frames. Thus, medium reservation increased latency as the time required to transmit the packets increased due to the RTS/CTS dialogue.

D. Energy-Latency Trade-Off

This scenario evaluates the existence of the energy-latency trade-off, described in Section III-C, on MANETs and WSNs. To analyse this effect, we implemented another omniscient routing protocol using the following rationale. A default transmission power (P, where its value indicates the number of the line on Table II, thus higher values of P indicate a higher transmission power) is selected from the set of options available on the radio. The protocol builds a minimum hop path that prioritizes links using transmission powers lower or equal than P. If there are two paths with the same length in hops, the one that uses the smallest amount of energy is chosen. The protocol uses transmission powers higher than P only if there is not any path from source to destination that uses only power levels under or equal to that limit.

We evaluate this trade-off in two scenarios, MANETs and WSNs. The first uses the radio model described in Section IV, where the energy consumed by each transmission power configuration varies up to a few percents, thus reducing the energy savings of using a smaller transmission power. The second model is based on the CC1000 [24] radio used in sensor networks. This low-power transceiver allows much more significant energy savings, as shown in Table III, since the amount of energy spendings of the various transmission powers differ by up to 66%.

MANET scenario: In this scenario we vary the number of nodes, as in previous scenarios. Since the results for all traffic types were quite similar, we present results only for the bursty traffic. To improve the legibility of the figures, we only show results for the transmission powers one, two and six.

Due to the small difference on the energy consumption from the maximum transmission power when compared to the smallest one (which is in the order of a few percents), the difference on energy consumption when the default transmission power was changed was not significant, as Figure 10 shows. In fact, the highest measured difference was slightly larger than 2%. However, the default transmission power significantly affects the average latency. Figure 11 shows that the average latency may vary by up to 500% on networks using a bursty traffic. This difference was less pronounced for the other two traffic types, however using the highest transmission power instead of the lowest reduced the average latency by up to 66%.

This scenario indicates that the energy-latency trade-off identified by Ammari and Das on WSNs does not seem to exist on MANETs. This is a very important result as, to our knowledge, all the existing TPC-aware protocols for MANETs try to minimize the energy consumption. Meanwhile, our study suggests that this is not the best strategy. It is advisable to build minimum hop count routes using TPC-aware links, as the average latency should be smaller when compared to minimum energy paths, and the difference in energy consumption will be in the order of a few percents.

Next, we used the covariance to identify which characteristic of the communication (the amount of collisions or the amount of hops) is more important to the overall energy consumption and latency. Since the covariance varied with node density, Table IV shows the range of values achieved, averaging the results over all transmission powers (since they performed similarly). The amount of collisions seems to be more significant than the amount of hops in the energy consumed and latency, which partially explains why there is not an energy-latency trade-off on MANETs.

WSN scenario: In this scenario we emulate a WSN for intrusion detection. Mica2 sensors equipped with cameras send live feeds to the AP, consisting of gray-scale images at a resolution of 64x64 pixels [25], sent every 20 seconds. Three of the nodes have detected suspect activities, and thus transmit data as described above, while all other nodes are silent. The packet size was set to 36 bytes, the maximum frame size on the Mica2 platform. All nodes are static, and are randomly placed on a field with an area of 1.2km$x$0.600km. In order to maximize hop count, the AP is placed at the position $(0, 300)$, while the transmitting nodes are placed at the positions $(1200, 0)$, $(1200, 300)$ and $(1200, 600)$. As mentioned previously, we model the radio found on Mica2 nodes, a Texas Instruments CC1000 transceiver, running at 38.4kbps. Although the radio provides 10 different power levels, in our experiments we only used six of them (see table III). The energy consumption on reception and idle modes of the radio are 28.8mW and 2.58mW, respectively. The simulations last for five minutes, allowing the network to reach a stationary state.

Name	Transmission Power	Power Consumption	Radio Range
P_{TX} 1	-20 dBm	25.8mW	42m
P_{TX} 2	-15 dBm	27.9mW	56m
P_{TX} 3	-10 dBm	30.3mW	75m
P_{TX} 4	-5 dBm	41.4mW	100m
P_{TX} 5	0 dBm	50.4mW	133m
P_{TX} 6	5 dBm	76.2mW	178m

TABLE III

RANGE AND ENERGY CONSUMPTION ON THE CC1000 RADIO.

Figure 12 shows the average energy consumption. Networks using higher default transmission powers consumed more energy, agreeing with Ammari and Das's model. The consumption is higher due to the use of less hops, which require a higher transmission power. The consumption for transmission powers five and six was constant for all the tested node densities, as all hops employed transmission powers below the maximum per-hop value. For smaller transmission powers, the energy consumed decreased with more nodes whenever larger routes could be found. This is seen when we compare Figure 12 against the average hop count, depicted in Figure 13. We also see that the highest transmission power consumes up to 35% more energy to deliver packets for networks with 300 nodes.

Since larger routes must traverse more hops, the average latency is more pronounced for smaller transmission ranges, as Figure 14 shows. The figure shows that the average latency quadruples for networks with 300 nodes when we reduce the default transmission power from one to six. Besides the larger number of hops that must be traversed, we found that the number of collisions may increase by up to 75% for the densest configuration (300 nodes). Next, we verified the covariance to identify the importance of the number of collisions and number of hops in the determination of the energy consumption and delay, as Table IV shows. Contrary to MANETs, the amount of collisions and hops seem to be as important to determine average energy consumption and latency.

Thus, the energy-latency trade-off seems to exist on WSNs. By carefully choosing the transmission power, we could reduce the average latency at the cost of a higher energy consumption by increasing the transmission power. Also, we could reduce the transmission power in order to reduce energy consumption, in turn increasing the average latency.

Variable	MANETs		WSNs	
	Latency	Energy	Latency	Energy
Collisions	$(0.7, 0.9)$	$(0.4, 0.8)$	$(0.3, 0.55)$	$(-0.4, -0.1)$
Hops	$(0.0, 0.4)$	$(-0.2, 0.5)$	$(0.1, -0.5)$	$(-0.6, 0.1)$

TABLE IV

CORRELATION OF COLLISIONS AND NUMBER OF HOPS ON THE ENERGY CONSUMED AND LATENCY OF PACKETS

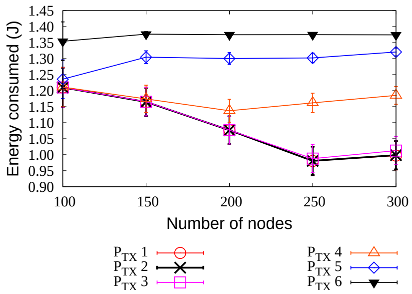

Fig. 12. Average energy consumption.

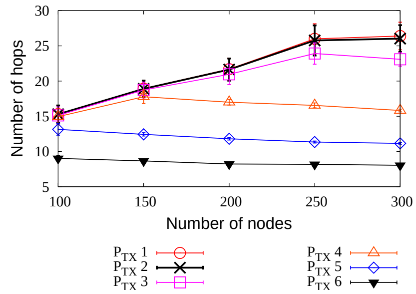

Fig. 13. Average number of hops.

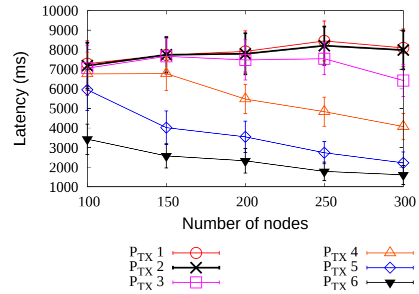

Fig. 14. Average latency.

E. Variable Data Rates

This scenario evaluates the effect of AMC on TPC-aware MANETs. In our point of view, AMC must be considered on minimum hop count routing protocols, since those protocols will tend to use nodes that are farther away from each other. As a consequence, the selected links will most likely have low data rates. Thus, we argue that TPC-aware routing protocols should consider the transmission power and the data rate of the links to build routes. In order to better understand the effect of AMC in routing, this scenario compares the performance of the three routing minimization functions described in Section IV-A.

The simulator was modified to support the four data rates mandated by the IEEE 802.11b standard. We simulate a 1km$x$2km area, varying the number of nodes from 10 up to 300 nodes, to show how the protocols behave when they must use longer hops due to very few nodes. Since the trends were similar for all traffic types, we present the results for the light traffic.

Figure 15 shows the average latency for the MHA and ME functions. We do not show the average latency of the MH function, around 700ms, in order to provide a better visualization of the difference among the two other functions. When compared to ME, MHA improves the latency by a few milliseconds, due to the use of faster links. The terrible performance of the MH function is due to the use of more distant neighbors, which employed smaller data rates. ME achieved latency results comparable of those of MHA. This is due to two reasons. First, the hop count of MHA is less than 0.1 hops larger than that of ME, as portrayed in Figure 16. Second, the data rates of MHA and ME are quite similar, 11Mbps and 9Mbps, respectively, as shown in Figure 17.

MH build routes with up to 0.4 less hops than ME and, for networks with less than 50 nodes, it uses up to 1.2 less hops than MHA. The sudden increase in the number of hops in MHA is due to an attempt to maintain a high data rate. As Figure 17 shows, the average data rate of the links selected by the MH function were almost 50% slower than that of MHA function for networks with 50 up to 300 nodes. For networks with less than 50 nodes, however, MHA had to resort to slower links to build its routes. Similarly, since ME had no close neighbors to choose from, it build routes using slower links.

Since ME tends to use the lowest transmission powers, thus selecting closer neighbors, it naturally builds routes that use higher data rates. When we compare MH against MHA, we see the importance of taking the data rate into account on minimum hop protocols, since those tend to select more distant nodes. While the minimum data rate of MHA was 11Mbps most of the time, the minimum data rate of the links traversed on MH and ME was 1Mbps and 4Mbps, respectively. The results above show that the data rate is an important parameter in TPC-aware networks, since it greatly influences the latency of the packets.

F. Discussion of the Results

Based on the results above, we summarise our findings, in order to aid researchers to quickly define which radio parameters must be simulated according to the characteristics of the target MANET.

Number of transmission levels: Should always be set to a limited amount of values, since an arbitrary model will always consume less energy and build larger routes than a more realistic model.

Existence of capture: Capture is important only on scenarios where the network load is high. However, event-based WSNs, where nodes rarely transmit data, could be simulated without modelling capture.

Medium Reservation: This factor should be modeled. Medium reservation increased the latency and energy consumption for all the characterized loads.

The energy-latency trade-off: Our results suggest that TPC-aware routing protocols in MANET should build minimum hop-count routes, and use TPC techniques to reduce the energy consumption on a per-hop basis, instead of using TPC-aware links to build minimum energy routes. On WSNs, however, minimum energy routes may reduce the energy consumption by up to 40%, but those savings come at the cost of a much higher average latency. Thus, while the energy-latency trade-off reported by Ammari and Das occurs in WSNs, it does not seem to exist on MANETs.

Variable data rate: This factor should be modeled on simulations. Since the state of the art on routing protocols does not consider the data rate of each link, results can vary significantly when the dynamic data rate is not modeled.

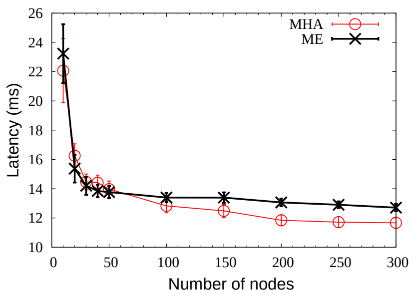

Fig. 15. Average latency.

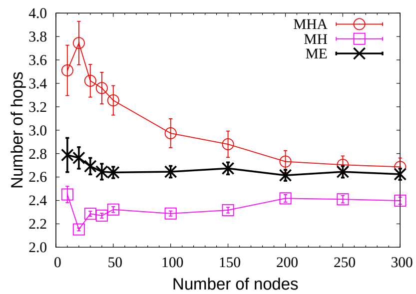

Fig. 16. Average number of hops.

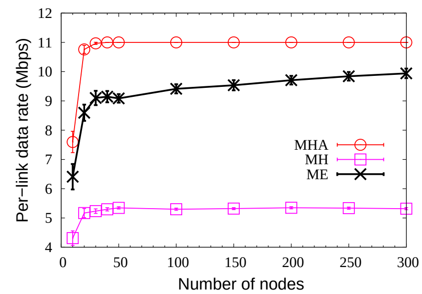

Fig. 17. Average data rate.

VI. Conclusions and Future Work

Due to the use of battery-powered nodes on mobile ad hoc networks (MANETs), energy consumption plays an important role in the design of networking protocols. One of the methods used to decrease energy consumption is transmission power control (TPC), a technique where the sender adjusts the output power so that the signal reaches the receiver at the minimum reception power required for the correct decoding of the signal. As MANETs use multi-hop paths, the issues of TPC must be considered on both link and network levels.

This work presented a simulation-based study on the effects of TPC techniques on the performance of MANETs under different channel models. The contributions of the paper are two-fold. First, we re-evaluated several hypothesis found on the TPC literature under a realistic radio model. This model allowed us to disprove that TPC techniques allow an energy-latency trade-off when applied on 802.11-based radios. Second, we made an incremental evaluation of radio features such as number of available transmission powers, use of medium reservation, existence of the capture effect and dynamic modulation and coding, showing how those characteristics affect the performance of TPC-aware networks. This work indicates how future research should model the wireless channel in order to achieve more realistic simulations. Finally, by varying the route selection strategy, we showed that TPC-aware routing protocols for MANETs should minimize hop count instead of minimizing energy consumption, as least hop count routes have higher throughput, at the expense of a marginal increase in energy consumption. This goes against existing work on TPC-aware routing protocols, which traditionally built minimum energy routes.

Due to our simulation-based approach, we were unable to verify whether TPC-aware links are more reliable than ordinary ones. We plan to characterize the amount of lost packets on TPC-aware nodes using experimentation. Another important factor is node mobility, which influences the accuracy of routing tables and increases the dynamicity of the transmission power. Finally, we plan to propose a TPC-aware routing algorithm, based on the analysis described in this work.

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