Ad Hoc Routing Under Randomised Propagation Models *

João Matos and Hugo Miranda

University of Lisbon
Faculty of Sciences
LaSIGE

Abstract. The deployment of mobile ad hoc networks is difficult in a research environment and therefore the performance of protocols for these networks has been mostly evaluated on simulators. A simulator must replicate realistic conditions and one of the most difficult aspects is the radio signal propagation model. The literature shows that many performance evaluations were conducted using propagation models that are not realistic for the expected application scenarios. This paper shows that the non-determinism present in some radio propagation models induce randomness which may compromise the performance of many protocols. To demonstrate the problem, this paper compares and discusses the performance of some routing protocols under different propagation models.

1 Introduction

Mobile Ad Hoc Networks (MANETs) are wireless networks with no fixed infrastructure and therefore are composed exclusively by the devices of the participants. All management and communication operations are assured by the participating devices. These networks are particularly relevant in scenarios where the deployment in advance of an infra-structure is not possible or desirable. Nodes communicate using their wireless network interfaces, which have a limited transmission range unlikely to cover all the nodes in the network. Message delivery is achieved by having nodes located between a source and a destination to retransmit the messages. Routing protocols are responsible for discovering a sequence of intermediate nodes (a route) that connects two endpoints.

Radio propagation considerably influences the performance of wireless communication systems, including ad hoc routing. The transmission path between two nodes can be a direct and unobstructed line-of-sight or a complex and strongly obstructed one, due to the presence of all kind of obstacles. Experimenting with wireless networks is usually done in simulated environments, because *i*) it is common for the number of devices involved to be high, *ii*) devices are often expensive and therefore it is wise to assure feasibility before deployment.

* This work has been partially supported by FCT multiannual fund and by project PATI (PTDC/EIA-EIA/103751/2008) through POSI and FEDER.

INForum 2010 - II Simpósio de Informática, Luís S. Barbosa, Miguel P. Correia (eds), 9-10 Setembro, 2010, pp. 379–390

There are many kinds of wireless networks, environments and radio technologies and all these aspects influence the effective signal propagation in the ether. As a consequence many radio propagation models have been devised. Unfortunately, some popular propagation models for network simulators do not account with multi-path propagation effects caused mostly by surrounding obstacles. The randomness caused by these unpredictable irregularities is frequently present in numerous types of radio wave propagation, including those used in most popular wireless network technologies, like IEEE 802.11 (WiFi).

Many ad hoc routing protocols ([1,2,3] to name a few) were tested under propagation models like *two-ray-ground* [4] and *free space* [5]. These propagation models are not adequate for testing realistic ad hoc networks (for example using WiFi technology in a region with obstacles). Therefore, the expected performance of many routing protocols may not be observed when used in a real deployment. This paper aims to highlight this problem through simulations by comparing the performance of three routing protocols using two different radio propagation models. Results confirm our expectations by showing a significant performance degradation in a more realistic propagation model. The paper also dissects these results and identifies the design characteristics of the protocols that make them more vulnerable. The paper is organised as follows: in Sec. 2 the routing protocols in comparison are presented. Section 3 describes the most relevant propagation models and Sec. 4 addresses the adaptation problems of routing protocols to specific radio propagation models. The evaluation results are discussed in Sec. 5 and in Sec. 6 the related work is presented.

2 Routing Protocols

Depending on their eagerness in populating routing tables, routing protocols for MANETs can be arranged in two broad categories: reactive and proactive. Reactive routing protocols are distinguished by having routes being discovered on-demand, while proactive routing protocols aim to keep their routing tables permanently up-to-date. For completeness, our study focused on protocols of both categories. The following presentation is oriented to the aspects relevant for our evaluation. The interested reader is referred to [1,2,3,6] for in-depth descriptions of these protocols.

2.1 Reactive Routing Protocols

In reactive routing protocols routing tables are filled and updated during route discovery operations, which are initiated only when a route to a certain destination is required and is absent on the routing table. The node requiring a route for an unknown destination broadcasts a *route request* message, disseminated to the entire network.The most simple and popular way to deliver a message to the entire network is to flood it, that is, to have all the nodes retransmitting it when it is received for the first time. This broadcast algorithm is called flooding and is used by many reactive routing protocols for route discovery operations.

When a node receives a *route request* message for the first time, it verifies if its routing table contains a route to the required destination and if not, continues the propagation of the *route request*. Otherwise, the node sends a point-to-point *route reply* message addressed to the source of the *route request*. The *route reply* message will follow the route created during the propagation of the *route request*. That is, each node broadcasting the *route request* message must keep track of the node from which it was received. The destination node also produces a *route reply* when a *route request* message is received.

Node's movement, network congestion and multi-path propagation effects frequently invalidate routes. *Route Error* messages are notifications addressed to the source of some data message and produced by intermediate nodes unable to deliver the message to the next hop.

In our study, the performance of reactive routing protocols was evaluated using two of the most representative routing protocols of this class, which are detailed below.

AODV The route request message of the Ad hoc On-demand Distance Vector (AODV) routing protocol [3] includes, among others, fields for the sender's address, destination's address and broadcast id. The pair <sender's address, broadcast id> of each *route request* message allow nodes to detect duplicates. Other fields, like *sender sequence number* and *destination sequence number*, allows nodes to determine the freshness of the route. The sequence number for each destination is stored in the routing table, together with the number of hops to the destination and the address of the *next hop*, that is, the node to whom messages addressed to the destination should be relayed.

Routes are learnt in the opposite direction of message propagation. That is, the reception of a route request or route reply message is used by nodes to learn a route to the sender of the message. The *next hop* for this route will be the node from which the message was received.

AODV purges from the routing table routes that have not been used for a predefined time. In addition, it updates its routing table if: *i*) the sequence number of the new route is strictly higher or; *ii*) the sequence number is equal but the number of hops to the destination is lower. One aspect of AODV very relevant for this paper is that every node replies only once to the same route request. This means that if a node receives the same route request from several neighbours, it replies only to the neighbour who first delivered the route request.

DSR The structure of the routing table in the Dynamic Source Routing (DSR) protocol [2,6] is significantly more complex as it stores complete routes. In addition, nodes cache multiple routes to any destination. This allows a faster reaction to routing changes given that there will be no additional overhead from a new route request operation. DSR data packets carry the full list of nodes that should be traversed to reach the destination.

During the propagation of a route request, each intermediate node appends its address to the header of the route request message, thus providing the complete sequence of intermediate nodes that lead to the destination.

One important aspect of DSR for our work, is that whenever a *route error* message is received by the source, it tries all the routes present in its cache, before starting a new route discovery operation. When a new *route request* message is disseminated, it carries information about the broken links found in the routes cached by the source. The network interfaces of nodes running DSR are expected to operate in promiscuous mode, receiving and interpreting every message sent by any neighbour. Listened messages are used to update node's routing table. Examples of applications of promiscuous mode are the learning of new routes listened from data packets and the removal of stalled routes learnt from snooping route error messages.

2.2 Proactive Routing Protocols

In proactive routing protocols every node maintains in its routing table an up to date list of all participants and routes to reach them. This is achieved by having nodes to periodically broadcast their routing tables.

Each node in the network maintains, for each destination, a preferred neighbour and each data packet contains a destination node identifier in its header. When a node receives a data packet, it forwards the packet to the preferred neighbour for its destination. The methods used to construct, maintain and update routing tables differ between various routing protocols.

The proactive routing protocol Destination-Sequenced Distance Vector (DSDV) [1] requires each mobile node to advertise its own routing table to its 1-hop neighbours. Routing tables include all available destinations with the respective routes and the number of hops. The entries in this list may change dynamically over time, so the advertisement must be made often enough to avoid unavailability problems. When significantly new update information is available, nodes transmit it immediately.

In a very large population of nodes, adjustments are likely to be made a short while after an exchange of complete routing tables. In order to reduce the amount of information exchanged, two types of packets are defined. One carries all the available information, and is called *full dump* and the other possesses only the information changed ever since the last *full dump*, called *incremental*.

3 Propagation Models

Propagation models are used in simulators to predict the received signal strength indicator of each packet received by a node. Propagation models that predict the mean signal strength for an arbitrary distance between two nodes are called *large scale* propagation models, because these distances may become very large. This section covers this type of propagation models and presents three common methods for received signal strength prediction.

The *path loss*, which represents signal attenuation as a positive quantity measured in dB, is defined as the difference between the transmitted power and the received power. Different propagation models may be distinguished by the method used to calculate the path loss between two nodes. Therefore, the received signal strength is predicted by the subtraction between the effective transmitted power and the path loss calculated.

The popular network simulator *ns-2*[1] in particular, creates a threshold variable which defines the minimum possible value of the Received Signal Strength Indicator (RSSI) with which a node is still able to receive a packet. Considering the propagation model in use, it then calculates the RSSI with which a packet was received by a node. If the value is smaller than the threshold, *ns-2* considers that the packet was not received by the node. The following sections present three popular distinct propagation models available in *ns-2*.

3.1 Deterministic Models

The free space propagation model [5] is a deterministic propagation model that defines the communication range as a perfect sphere around the transmitter. In free space only one clear and unobstructed line-of-sight path between the transmitter and receiver exists. The received signal strength indicator is calculated by the Friis free space equation $Pr(d) = \frac{PtGtGr\lambda^2}{(4\pi)^2 d^2 L}$, where d is the distance between nodes, P_t is the transmitted power signal, G_t and G_r are the antenna gains of the transmitter and the receiver respectively, L is the system loss and λ is the wavelength in meters. The free space propagation model is considered accurate to predict *rssi* for satellite communication systems and microwave line-of-sight radio links [4].

In a mobile radio channel, a single direct path between the base station and a mobile node is seldom the only physical means for propagation, and hence free space is in most cases inaccurate when used alone [4]. Instead of having a single line-of-sight path between two nodes, the two-ray ground reflection model considers both the direct path and a ground reflection path, as shown in Fig. 1. The total received electrical field (E_{TOT}) is the result of the direct line-of-sight component (E_{LOS}) and the ground reflected component (E_g). This model gives more accurate prediction at a long distance than the free space model [4]. However, the two-ray ground reflection model is also deterministic when predicting the received signal strength indicator. It is calculated using the formula $P_r(d) = \frac{PtGtGrht^2hr^2}{d^4 L}$, where h_t and h_r are the heights of the transmit and receive antennas respectively. Like in free space, the communication range in the two-ray ground reflection model is an ideal circle, centred at the transmitter. This model has been considered reasonably accurate for mobile radio systems that use tall towers and also for line-of-sight microcell channels in urban environments [4].

3.2 Randomized Models

The models above do not consider the fact that the surrounding clutter may be very different at two different locations having the same distance to the source

[1] http://www.isi.edu/nsnam/ns/

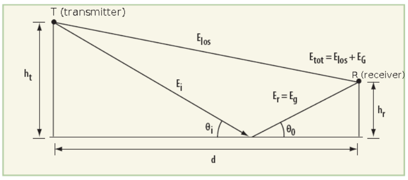


Fig. 1. Two-ray Ground Reflection Model [4]

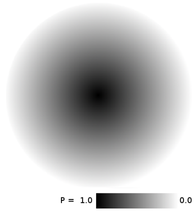


Fig. 2. Log-normal Shadowing: (P is the probability of receiving a packet)

or even for the same location at different moments in time. Therefore their use is inappropriate, in various scenarios because the received power is actually affected by unpredictable multi-path propagation effects. The Log-normal shadowing model considers that the signal fades log-normally and randomly. That is, the path loss increases log-normally with distance but a random component, whose influence becomes more visible as the path loss increases, must also be considered. In practice, the model results in having nodes located farther from the transmitter possibly receiving packets while some nodes located closer might not. This also means that the probability of a node receiving a message becomes smaller as the distance increases, as illustrated in Fig. 2.

Like most propagation models, the shadowing propagation model determines the received power at distance d removing the calculated path loss value from the transmitted power value, as shown in Eq. 1. However, as shown in Eq. 2, the path loss is divided in two parts. One part is the log-distance path loss model and predicts log-normally the mean received power at distance d, denoted by $\overline{PL}(d)$ (Eq. 3). This part uses a close-in distance d_0 as a reference. The second part of the model consists on the variation of the received power at a certain distance. It is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (also in dB). Therefore, considering Eq. 2, the variable $X\sigma$ represents the random part of the model and the variable $\overline{PL}(d)$, the deterministic part.

$$P_r(d)[dBm] = \underbrace{P_t[dBm]}_{\text{Transmitted power}} - \underbrace{PL(d)[dB]}_{\text{Path loss}} \tag{1}$$

$$PL(d)[dB] = \underbrace{\overline{PL}(d)}_{\text{log-normal path loss}} + \underbrace{X\sigma}_{\text{Random path loss}} \tag{2}$$

$$\overline{PL}(d) = \overline{PL}(d_0) - 10\beta \; log(\frac{d}{d0}) \tag{3}$$

The log-normal distribution describes the random shadowing effects which occur over a large number of measurement locations which have the same distance to the source, but have different levels of clutter on the propagation path [4]. The close-in reference distance d_0, the path exponent β and the standard deviation σ, statistically describe the model for an arbitrary location. It should be noted that, in contrast with two-ray ground and free space, log-normal shadowing does not assume the communication range to be a perfect sphere.

4 Routing Protocols and Propagation Models

Energetic, communicational and computational resources of the devices in a MANET are usually limited. Networking operations, namely transmissions are expensive in terms of energy consumption [7] and routing protocols aim to reduce them to a minimum. Metrics used by routing protocols usually combine cost and congestion, evaluated respectively by the number of hops and delay. The randomness imposed by fading effects is usually neglected and the protocols tend to adapt poorly to shadowed environments. In this paper, we identify two adaptation problems that can be observed in some of the most popular routing protocols for MANETs.

Shadowing induced link asymmetries [8,9] In the shadowing model, neighbour nodes farther from the source have a low probability to receive the route discovery message than closer ones (as illustrated in Fig. 2). However if a node has many neighbours, chances are that at least one of the distant neighbors does receive it. Additionally, the route discovery message usually travels through multiple hops and therefore, it is likely for a route to include at least one such "weak" (long) link.

Surprisingly, routing protocol metrics (like those used by AODV, DSR and DSDV) tend to favour routes that include weak links as they are expected to have a lower number of hops (thus reducing cost) and to be discovered faster (which is interpreted as a sign of lower congestion). Although this route would indeed be preferable, the weak link has the same low probability of delivering the route reply in the reverse path. Probabilities suggest that in most cases, the route ends up not being established. When the waiting period expires, the source will be required to start a new route discovery operation which might be unsuccessful for the same reason.

Despite not having *route request* nor *route reply* messages, proactive routing protocols are also affected by this problem. Nodes exchange routing information through periodic messages which are likely to contain routes including some weak link. Again, these routes are likely to be preferred because metrics suggest they have a better performance.

Route stability in a shadowed environment The second problem appears after a route between two nodes has been established. In deterministic models like *free-space* and *two-ray ground* if a node is located within the transmission range of another, it will certainly receive every packet sent. In practice, a route does not break unless some node that composes it moved away or a congestion problem made some node believe that its neighbour moved. On the other hand, a propagation model such as *shadowing* does not guarantee that a node close enough to the sender will receive the message. Such transient problems are usually handled at the link layer level, at the expenses of additional traffic produced by retransmissions. However, in some cases, the time took by the link layer to deliver the packet can be misinterpreted by the routing protocol as a sign of route breakage. More frequent route invalidation result in additional traffic produced by route errors and route discoveries.

5 Evaluation

To validate the two hypothesis stated in Sec. 4, we analyse the performance of three routing protocols, AODV, DSR and DSDV under two radio propagation models, *two-ray ground* and *shadowing*. The goal is to look for patterns that appear in the performance of the routing protocols while using *shadowing* propagation model and are not present when *two-ray ground* is used. Both *free space* and *two-ray ground* are deterministic propagation models and represent the transmission range as an ideal sphere and therefore including the two models in our evaluation would not provide any additional contribution. Three routing protocols, two reactive and one proactive are used to evaluate if the problems are exclusive to one particular protocol or class of routing protocols. Results are obtained using v. 2.34 of the *ns-2* network simulator. This simulator already implements all the propagation models and routing protocols experimented.

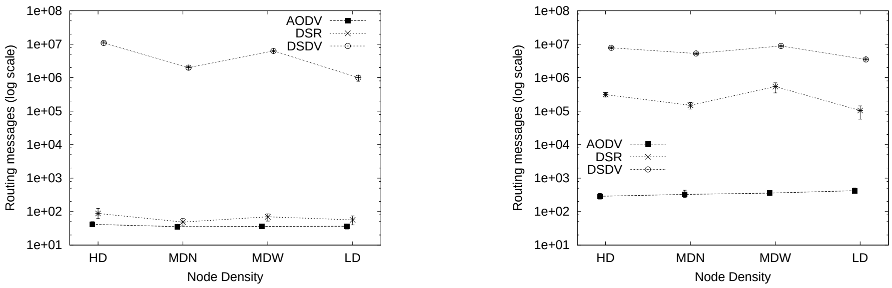
Simulation Test Bed The performance of routing protocols is affected by a myriad of factors like mobility and congestion. The experiments presented in this paper aimed to reduce to a minimum the interference on performance of external factors not strictly related with the propagation model. Therefore, we defined a baseline scenario of quasi ideal conditions for any of the protocols. To avoid congestion, traffic is kept constant at a low rate of one 512 bytes data packet per second. To enforce route discovery operations the source and destination of the packets changes every 60 seconds. Nodes do not move for the entire extent of the simulations, thus preventing "legitimate" route errors and additional route discovery operations.

Experiments consist of 160 simulations for each pair of routing protocol and propagation model. Each simulation has the duration of 1800 seconds. To evaluate the impact of the number of neighbours and route length on the performance of each pair, the simulations have been arranged in 4 different scenarios, presented in Tbl. 1. In each simulation nodes are randomly deployed over a region with the specified dimension according to an uniform distribution. An uniform distribution is also followed on each simulation to define the traffic sources and destinations. To make comparisons acceptable, the exact same conditions of node deployment and traffic are used for every pair of routing protocol and propagation model. Plots present the average of the 40 simulations for each <routing protocol,propagation model,scenario> tuple. Error bars depict the values observed for the 10% lowest and highest simulation.

In the two-ray ground propagation model each node was configured for a transmission range of $250m$. The shadowing simulations test an outdoor shadowed urban area with a path loss exponent β of 2.7 and a standard deviation σ

Name	Stands for	Density	Nodes	Region Size
HD	High Density	$3750m^2.node$	200	$1500m \times 500m$
MDN	Medium Density Narrow area	$7500m^2.node$	100	$1500m \times 500m$
MDW	Medium Density Wide area	$7500m^2.node$	200	$3000m \times 500m$
LD	Low Density	$15000m^2.node$	100	$3000m \times 500m$

Table 1. Comparison of the configurations experimented



(a) Two-ray ground

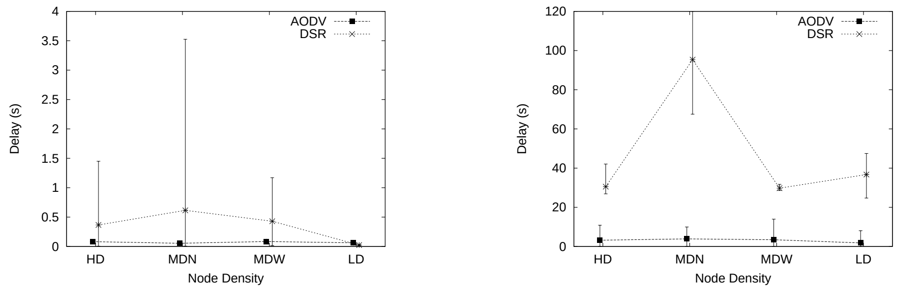
(b) Shadowing

Fig. 3. Route discovery messages

of 4, with a 95% of correct reception at $250m$ [10]. These are values commonly used in ad hoc routing experiments ([8,11] for example). We recall that an exact range cannot be defined for the shadowing propagation model. Therefore, with some probability, some nodes closer than $250m$ from the transmitter do not deliver a packet while others, more distant will.

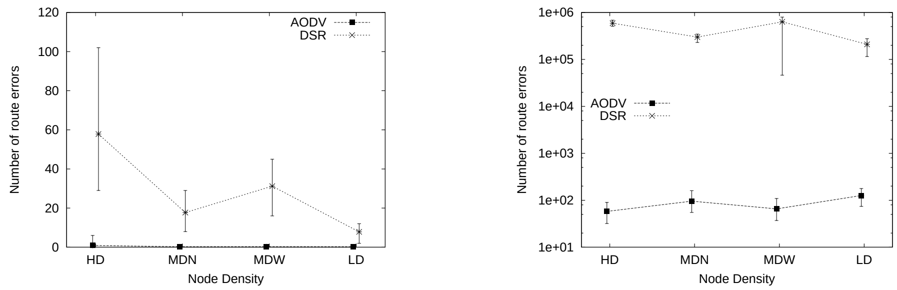
Evaluation Results The number of route request messages originated by each tested protocol are depicted in Fig. 3. For DSDV, the plots depict the number of periodic route advertisement messages that is characteristic of proactive routing protocols. The figures show that in all three protocols, considerably more routing messages are originated when the shadowing propagation model is used. This is more significant on DSR that suffers an increase of more than 1000 times.

Confirmed the negative impact of the shadowing propagation model on the number of route discovery operations, we proceed to investigate the origin of the problem. Figure 4, that depicts the average time between the triggering of a route discovery operation and the reception of the first route reply, confirms the presence of the *Shadowing induced link asymmetries* problem. Knowing that no obstacle is made to the message propagation speed by any of the propagation models, an increased delay in the delivery of the route replies can only be attributed to the need of the route discovery initiator to perform multiple retries. Again, the problem is more visible in DSR, what follows naturally from the observed increase in the number of route requests that have been initiated. We note that for DSDV the delay is always null because routes are immediately available on the route cache of any node.



(a) Two-ray Ground (b) Shadowing

Fig. 4. Route discovery latency



(a) Two-ray Ground (b) Shadowing

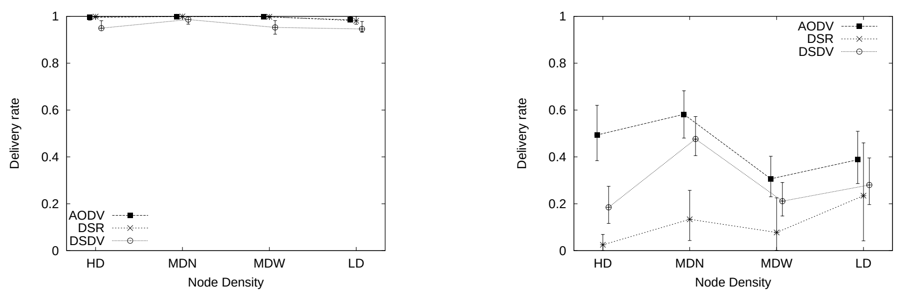
Fig. 5. Number of route errors

However, *Shadowing induced link asymmetries* is not the only problem affecting DSR and AODV. Figure 5, counts the number of observed route error messages and confirms that in the shadowing propagation model routes: *i*) are equally established and *ii*) break far more often than in deterministic propagation models. Because nodes do not move during the simulation, *ii*) supports the conclusion that the *Route stability in a shadowed environment* problem is equally present. Again DSDV is not accounted for this metric because route invalidation is detected within the periodic exchange of routing information.

The consequences of the problems discussed above are depicted in Fig. 6. In Fig. 6(a) all protocols present an average delivery over 95% for all topologies. On the other hand, the delivery ratio in Fig. 6(b) is bellow 60% for AODV, 50% for DSDV and 30% for DSR.

6 Related Work

In [8] a comparison of these three routing protocols for Wireless Sensor Networks under *two-ray ground* and *shadowing* propagation models was also preformed.



(a) Two-ray Ground (b) Shadowing

Fig. 6. Delivery rate

However, the effects induced by the shadowing propagation model described above are not identified nor described in the paper and the analysis presented does not provide the same conclusions as this paper. The authors focus mostly on the properties of the wireless sensor network studied and give little attention to the radio propagation models and to their relevance in routing. In addition, the delivery rate is the only metric presented and therefore does not support the conclusion that the shadowing problems described above are actually present. The authors continued their work and presented a similar study for Mobile Event using AODV [11].

Solutions for these effects are very few. Studies about the minimum node density required to achieve a connected large-scale ad hoc network, where every node has the same transmitting and receiving capabilities under a shadowed environment are presented in [12,9]. The authors in [13] created a sub-layer between the network and the MAC layer that provides a bidirectional abstraction of a shadowed environment for routing protocols. Another example of attenuation for these problems was presented on [14] where the authors propose a model for estimation of the bit error rate for each link made available to a node. The use of MIMO devices and multiple frequency networks may diminish considerably the problems discussed in this paper. However, transmission errors are an integral part of the wireless propagation medium and are not expected to be fully avoided.

7 Conclusions and Future Work

Mobile ad hoc networks (MANETs) are a promising technology for a number of scenarios. However, they present a networking environment that is considerably different of what can be found in wired networks. An effective deployment of MANETs is not possible without a realistic estimation of the performance of a number of protocols that are fundamental for MANETs expected applications. This paper compared the performance of 3 routing protocols when distinct signal propagation models are simulated. The paper shows that all protocols have a significant performance degradation when the log-normal shadowing propagation model is used. Unfortunately, this is the most realistic model for expected MANET deployment scenarios.

As future work, authors plan to extend this study to other protocols and to devise mechanisms that may help to attenuate the difficulties observed by these protocols to cope with the shadowing propagation model. The apparently better resilience of AODV to transient connectivity in comparison with DSR will be used as an important guideline in our future work.

References

1. Perkins, C.E., Bhagwat, P.: Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In: SIGCOMM '94: Proc. of the Conf. on Communications architectures, protocols and applications. (1994) 234–244
2. Johnson, D.B., Maltz, D.A., Broch, J.: DSR: The Dynamic Source Routing Protocol for Multi-Hop Wireless Ad Hoc Networks. In: Ad Hoc Networking. Addison-Wesley (2001) 139–172
3. Perkins, C.E., Royer, E.M.: Ad-hoc on-demand distance vector routing. In: Procs. of the 2nd IEEE Works. on Mobile Comp. Systems and Applications. (1999) 90–100
4. Rappaport, T.: Wireless Communications: Principles and Practice. Prentice Hall PTR (2001)
5. Friis, H.T.: A note on a simple transmission formula. Proc. IRE **34** (1946)
6. Johnson, D.B., Maltz, D.A.: Dynamic Source Routing in Ad Hoc Wireless Networks. In: Mobile Computing. Kluwer Academic Publishers (1996) 153–181
7. Feeney, L.M., Nilsson, M.: Investigating the energy consumption of a wireless network interface in an ad hoc networking environment. In: IEEE Infocom. (2001) 1548–1557
8. Yang, T., Ikeda, M., De Marco, G., Barolli, L.: Performance behavior of AODV, DSR and DSDV protocols for different radio models in ad-hoc sensor networks. In: Parallel Processing Workshops, 2007. ICPPW 2007. Int'l Conf. on. (2007)
9. De Marco, G., Longo, M., Postiglione, F.: Connectivity of ad hoc networks with link asymmetries induced by shadowing. Communications Letters, IEEE **11**(6) (2007) 495 –497
10. Greis, M.: The ns manual (2010)
11. Yang, T., Ikeda, M., Barolli, L., Durresi, A., Xhafa, F.: Performance evaluation of wireless sensor networks for different radio models considering mobile event. In: Complex, Intelligent and Software Intensive Systems (CISIS), 2010 Int'l Conf. on. (2010) 180–187
12. Bettstetter, C., Hartmann, C.: Connectivity of wireless multihop networks in a shadow fading environment. Wirel. Netw. **11**(5) (2005) 571–579
13. Ramasubramanian, V., Chandra, R., Mosse, D.: Providing a bidirectional abstraction for unidirectional ad hoc networks. In: INFOCOM 2002. 21st Joint Conf. of the IEEE Computer and Communications Societies. Proc. IEEE. Volume 3. (2002) 1258–1267
14. Agrawal, R.: Performance of routing strategy (bit error based) in fading environments for mobile adhoc networks. In: Personal Wireless Communications (ICPWC). IEEE Int'l Conf. on. (2005) 550–554