# Impact of Propagation Factors on Routing Efficiency in Wireless Mesh Networks: A Simulation-based Study

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*Abstract*—**The low installation and maintenance costs, self-healing abilities and the ease of development are some of the qualities that make the multi-hop wireless mesh network a promising alternative to conventional networking in both – rural and urban areas. This paper examines the performance of such a network depending on environmental propagation conditions and the quality of applied routing protocols. This aim is addressed in an empirical way, by performing repetitive multistage network simulations followed by a systematic analysis and a conclusive discussion. This research work resulted in the implementation of an experiment and analysis tools, and a comprehensive assessment of a group of simulated wireless ad-hoc routing protocols.**

***Keywords-routing protocol; simulation; wireless mesh network; propagation shadowing***

## I. INTRODUCTION

The object of these investigations is the wireless mesh network (WMN). It is a multi-hop network that consists of stationary mesh routers, strategically positioned to provide a distributed wireless infrastructure for stationary or mobile mesh clients over a mesh topology [1]. WMN provides more robust, adaptive and flexible wireless Internet connectivity to mobile users compared to conventional local wireless networks (WLAN) or mobile ad hoc networks (MANET). It offers relatively low installation and maintenance costs, self-configuration and self-healing ability, thus ensuring more reliable connection and enlarging the covered area [2].

Routing is a crucial factor influencing connectivity and information exchange across the network. The flexibility, self-configuring and healing, as well as general performance of WMNs is highly dependent on the choice of a routing protocol and the quality of its implementation.

The objective of these investigations is to evaluate the performance of WMNs influenced by propagation factors referred to as signal shadowing. The evaluation is based on network simulations applying a group of commonly used WMN routing protocols, containing the Highly Dynamic Destination-Sequenced Distance-Vector (DSDV), the Ad hoc On-Demand Distance Vector (AODV), the Optimized Link State Routing (OLSR) and the Hybrid Wireless Mesh Protocol (HWMP). The analysis and discussion requires collating the protocols and conducting a comparison by experimentally simulating scenarios of environments with different propagation conditions. The result is an assessment of protocols suitability for the WMN and an evaluation of the overall network performance influenced by propagation conditions.

There have been conducted numerous researches investigating wireless network's performance with respect to the issue of routing [2][3]. A similar comparative evaluation of routing protocols was conducted by Zakrzewska et al. [13]. This work extends previous research in WMN routing by investigating the influence of propagation factors.

The rest of the paper is organized as follows: In Section II, the considered protocols are briefly described. Section III presents the experiment environment and simulation scenarios. Section IV shows the results and discusses the propagation impact. The final remarks appear in Section V.

## II. ROUTING IN WMN

The investigated routing protocols are used in 802.11b/g/n standard based WMNs. The selection of DSDV, AODV, OLSR and HWMP was dictated by the intention to investigate a wide spectrum of approaches towards topographical routing. These protocols can be divided into the classical groups of distance vector and link state routing protocols, as well as hybrid protocols that have characteristics of both. The common WMN routing protocols differ also in terms of the events triggering the routing information exchange. Some protocols use a proactive mechanism repeating broadcasts in regular intervals of time. Others exchange the information in reaction to current data transmission and other events.

### *A. DSDV*

DSDV is historically the first of the investigated routing protocols. It operates on ad hoc networks induce inferring a cooperative engagement of mobile hosts without a required intervention of any centralized access point [3]. It specifies each mobile host as a router, which advertises its view of the topology to other mobile hosts within the network [4], by periodically and incrementally broadcasting own routing table entries. DSDV determines the shortest route to a destination, i.e., a route with least intermediate hops.

DSDV construction is based on the basic Bellman Ford (BF) routing mechanisms, as specified by routing internet protocol (RIP), adjusting it to a dynamic and self-starting network mechanism required in ad hoc networks [4]. The modifications concern, e.g., poor looping properties, such as the counting to infinity problem. Furthermore, in order to damp out fluctuations in route table updates DSDV also includes a sequence number and settling-time data.

There are significant limitations in DSDV protocol, i.e., it provides only a single path between each given source and destination pair [5]. Furthermore, the protocol's performance is highly dependent on selected parameters of periodic update interval, maximum value of the settling time and the number of update intervals. These parameters likely represent a trade-off between the latency of valid routing information and excessive communication overhead [5].

### *B. AODV*

The AODV routing protocol offers the ability of quick adaptation to dynamic link conditions, low processing and memory overhead, low network utilization, and determines unicast routes to destinations within the ad hoc network. Similarly to DSDV, AODV uses destination sequence numbers to ensure the elimination of loops [6], but unlike DSDV, it does not require nodes to maintain routes to destinations that are not active in communication.

The AODV operations require Route Request (RREQ) messages, to be disseminated among a range of network nodes [6]. Despite from RREQ the AODV protocol defines the Route Reply (RREP), and Route Error (RERR) routing messages improving the efficiency of finding routes.

The on-demand character of the protocol implies that as long as the endpoints of a communication connection have valid routes to each other, no routing messages need to be sent. The information is kept in route tables, which (like in DSDV) store entries for all, even short-lived routes. Among the added fields of table entries are the valid destination sequence number flag and the list of precursors [6].

AODV is designed for use in networks, where the nodes can all trust each other, either by use of preconfigured keys, or based on known fact of no malicious nodes. It has been designed to improve the wireless network scalability and performance and eliminate overhead on data traffic.

### *C. OLSR*

OLSR protocol is an adaptation of the wired Link State Routing (LSR) algorithm, specifically designed to serve the needs of mobile ad hoc networks (MANET) [7]. The main adjustments tackle reduction of administrative data exchange and increase the overall protocol performance.

Each router in an OLSR routed network owns a complete representation of the whole network topology and maintains this information periodically by exchanging topology information with other nodes. This makes OLSR a member of the proactive and link state routing algorithms family.

OLSR exchanges information by the means of messages HELLO and Topology Control (TC) [7]. They are used to sense the links between nodes in direct neighborhood. Based on responses from the other nodes each node selects an individual subset of neighbors, which are from then on referred to as Multipoint Relays (MPR). MPR’s task is to execute the information exchange called flooding in its part of the topology. Therefore, each of the MPRs sends TC-messages containing local topology information to their respective MPRs, while forwarding received topology information to their non-MPR neighbors [7]. Hence, OLSR ensures a complete distribution of routing information, and limits the flooding data overhead only to MPR nodes. This design aims to lower administrative data exchange and improve scalability to network size and density.

Although OLSR is a young protocol, it is already used as a major WMN routing protocol e.g., by the Freie Funknetze in Berlin, Germany. It is criticized, though, for its large energy consumption due to constant data exchange and large topology databases.

### *D. HWMP*

The HWMP is a mesh routing protocol that combines the flexibility of on-demand routing with proactive topology tree. The reactive and proactive elements of HWMP are combined in order to enable optimal and efficient path selection in mesh networks (with or without infrastructure).

The HWMP protocol uses a set of protocol primitives, generation and processing rules taken from AODV, adapted for Layer-2 address-based routing and link metric awareness. The AODV mode is used for finding on-demand routes in a mesh network, while the optional proactive mode sets up a distance vector tree rooted at a single root mesh node [8].

The control messages in HWMP are the RREQ, RREP, RERR – introduced in AODV, and an additional Root Announcement (RANN) message. The metric cost of the links determines which routes HWMP builds. The needed information is propagated between mesh nodes in the metric fields of RREQ, RREP and RANN messages [8]. The loop free routing is ensured by the use of the sequence numbers.

In the experimental phase of this research, only the on-demand mode of HWMP is enabled, thus it is qualified as a reactive routing protocol.

## III. SIMULATION MODELING

The group of chosen routing protocols is compared based on an experiment using ns 2.34 network simulator (licensed for use under version 2 of the GNU General Public License). The choice of this simulator is motivated by its advantages, among which are: open source code, variety of implemented protocols and contributed code [10], as well as the reliability confirmed by the common usage for research purposes [13].

The simulated scenarios represent a structure of a hybrid WMN [9]. This means that all nodes have the mesh routing capabilities. The backbone of the network is formed by more powerful and completely stationary routers covering the topology in shape of a regular square grid. They provide the wireless infrastructure to the mobile users placed in random locations, which also support meshing and improve the internal network coverage [9].

Apart from mobility, router and mobile node properties differ in the matter of transmission capabilities, namely the transmitting power and the receiving threshold. On the sending side of communication, the initial packet signal power is regulated by a transmitting power value [10]. The receiving is limited by a threshold, which is assigned to a wireless node and determines the minimum value of packet's signal power required to succeed with its delivery. If the packet's signal power at the destination node does not reach the receiving threshold value, it is marked as error and dropped by the Media Access Control (MAC) layer [10].

### A. Radio Signal Propagation

The signal power fluctuates in a way determined by the phenomenon of radio wave propagation [11], which leads to the next issue of simulating wireless communication, namely radio propagation models. In general, these models predict the received signal power of each packet. There are three propagation models in *ns* [10].

The free space model assumes ideal conditions with a clear line-of-sight between the transmitter and the receiver [10]. This model represents the communication range as a circle around the transmitter. If a receiver is within the circle, it receives all packets. Otherwise, it loses all packets.

The two ray ground reflection model gives a more accurate prediction at a long distance than the free space model, based on considering both – the direct- and ground reflection paths. Still, this model also predicts the received power as a deterministic function of distance representing the communication range as an ideal circle (Fig. 1).

Those are the acceptable and commonly used simplifications of radio wave propagation for most of simulation based research. However, an attempt to investigate realistic conditions requires determining the received power at certain distance by a more complex computation. It is due to multipath propagation effects, which are also known as fading effects. These are taken in consideration in the shadowing propagation model [10]. This model redefines the calculation of the mean received power at a distance, making it dependent on the value called path loss exponent, which also enables a user to manipulate the propagation mechanism in simulations.

The signal power is reduced gradually with raising distance from transmission source, representing the communication range as a fuzzy circle. The diagrams (Fig.. 1, 2) were developed for the *ns* simulator and published by the Institute of Telematics at the Hamburg University of Technology, Germany to demonstrate the differences between propagation models. The upper graph shows the probability of receiving a packet by the middle horizontal line of nodes. The other graph is a 2D area plot representing the probability of receiving packets as grayscale points, where the darker the shade is – the higher the probability.

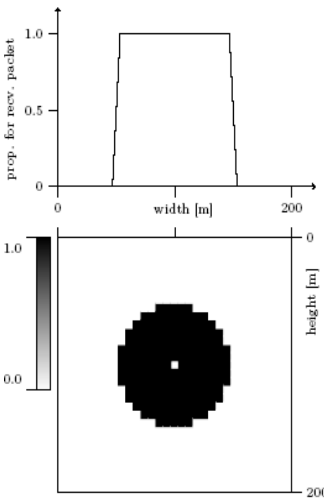


Figure 1. Probability of receiving packet – two ray ground model.

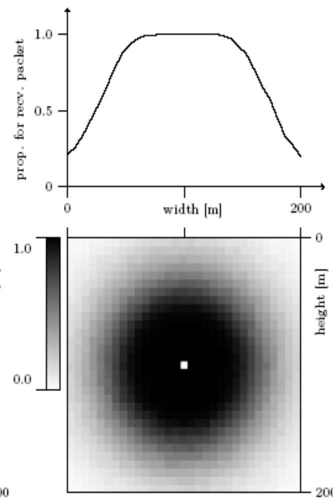


Figure 2. Probability of receiving a a packet – the shadowing model.

The shadowing model (Fig. 2) fulfills the description of IEEE 802.11 physical layer definition, which implies using a medium that has no readily observable boundaries, outside of which stations with conformant physical layers transceivers are known to be unable to receive network frames [11].

Furthermore the shadowing model introduces the shadowing deviation factor, which reflects the variation of the received power at a certain distance by time-varying and asymmetric propagation properties [10][11]. This prevents unrealistic representation of communication range as a circle, which was the case for other propagation models. It is also most probably the only way to simulate the presence of physical obstacles causing the signal power fluctuation in wireless network topologies. The intensity of this fluctuation is controlled by the shadowing deviation parameter [10].

## IV. RESULTS DISCUSSION

In this section, the performance of four investigated routing protocols is compared based on the WMN simulations with User Datagram Protocol (UDP) traffic. The simulations were carried out for the hybrid WMN topologies with the following settings:

| | | |
|---|---|---|
| Topology size | width | - 300m |
| | length | - 1200m |
| Amount of nodes | total | - 58 |
| | mobile | - 36 |
| | backbone | - 22 |
| Mobile node speed | maximum | - 5m/s |

The experiments were performed in order to observe the influence of two varying propagation parameters:

| | | |
|---|---|---|
| Shadowing deviation | min. 3 | - free space |
| | max.12 | - outdoor, very obstructed |
| Path loss exponent | min. 2.0 | - free space |
| | max. 4.4 | - urban shadowed area |

The performance is measured using metrics well describing performance of wireless networks [12][13]. The choice of metrics was dictated by the need of both – precise analysis as well as legible and intuitive representation.

Delivery ratio (DR) – the percentage of successfully delivered packets calculated as the total amount of data packets received at the destinations, divided by the amount of all data packets generated by the sources [12].

End to end delay of data packets (EED) – the average time passing from the moment of sending a data packet to its delivery, measured in milliseconds [13], including all delays such as route discovery latency, interface queuing and retransmissions, as well as propagation and transfer times [12]. The delay for individual hops is not measured.

Normalized routing load (RL) represents the relative content of routing packets. Here it is expressed as the amount of all sent and forwarded routing packets divided by amount of delivered data packets, thus each hop-wise transmission of a routing packet is counted [12].

 ISBN: 978-1-61208-183-0 

System throughput (ST) – the aggregate amount of data measured in bytes delivered at all nodes in a given period of time. The unit of the AT is kilobyte per second. In opposition to the received throughput (RT) metric [12], the ST reflects the summary amount of both – data and routing traffic.

## A. *Experiment 1. Impact of the shadowing deviation*

The results are collated in diagrams (Fig. 3), where each plot represents the performance of one routing protocol.

The packet DR reaches the maximum, i.e., most desired value of nearly 65% for minimum shadowing deviation, referring to environments with a clear line of sight (e.g., a factory). It holds true for all tested routing protocols. Increasing shadowing deviation lowers the DR. The decrease for the HWMP exceeds 40%; it is smaller for AODV – ca. 35%, whereas for OLSR and DSDV protocols it does not reach 30%. Nevertheless, the DSDV protocol is visibly the least effective – offering more than twice smaller DR in comparison to any other protocol. The favorites are AODV – for the highest DR in this experiment and OLSR – for slightly lower but more stable DR.

The same two routing protocols are leading, taken into account the EED. The HWMP and DSDV plots show similar results, mostly between 4 and 5s. These delays are over two times longer than for AODV protocol. The unquestionably best EED times are reached using OLSR protocol.

The results for OLSR seem implausibly small in comparison to other protocols, however revising the analysis procedure as well as manual analysis of parts of trace files confirms correctness of these EED outcomes based on simulations performed using the ns simulator.

AODV and OLSR produce comparable amount of routing packets sent per one successfully delivered data packet. For AODV it grows from circa 1.5 routing packets for shadowing deviation equal to 3, to almost 4 for maximal deviation. The range for OLSR is smaller but the values are higher – from 2.4 to 4.3. This amount for HWMP is twice smaller; also its increase trend is not as strong. The RL is smallest and nearly stable for DSDV routing protocol. That property corresponds with the proactive character of this routing protocol. Nevertheless, the benefit of a small amount of DSDV routing packets is overweighed by the disadvantage of their large size.

ST reflects the network load and it is not predestined to represent the speed of data transmission. The complete observation requires collating ST versus the DR and RL metrics. The largest ST of almost 1.7Mbps, and thus the greatest network load is generated by the DSDV protocol. This result confronted with low DR puts DSDV in the last place. The correlation with stable and low RL leads to an interesting finding. The amount of successfully transmitted data is small; the number of generated routing packets – smallest of all; the ST on contrary is the biggest. Then the size of the broadcasted routing information must be very large. The second largest ST, circa 1.1Mbps is generated for the HWMP, followed by 600 to 700kbps for the AODV protocol. The smallest result is reached using the OLSR.

This observation points to the conclusion that the optimal network performance for simulated scenarios is reached using OLSR, and the worst for DSDV protocol.

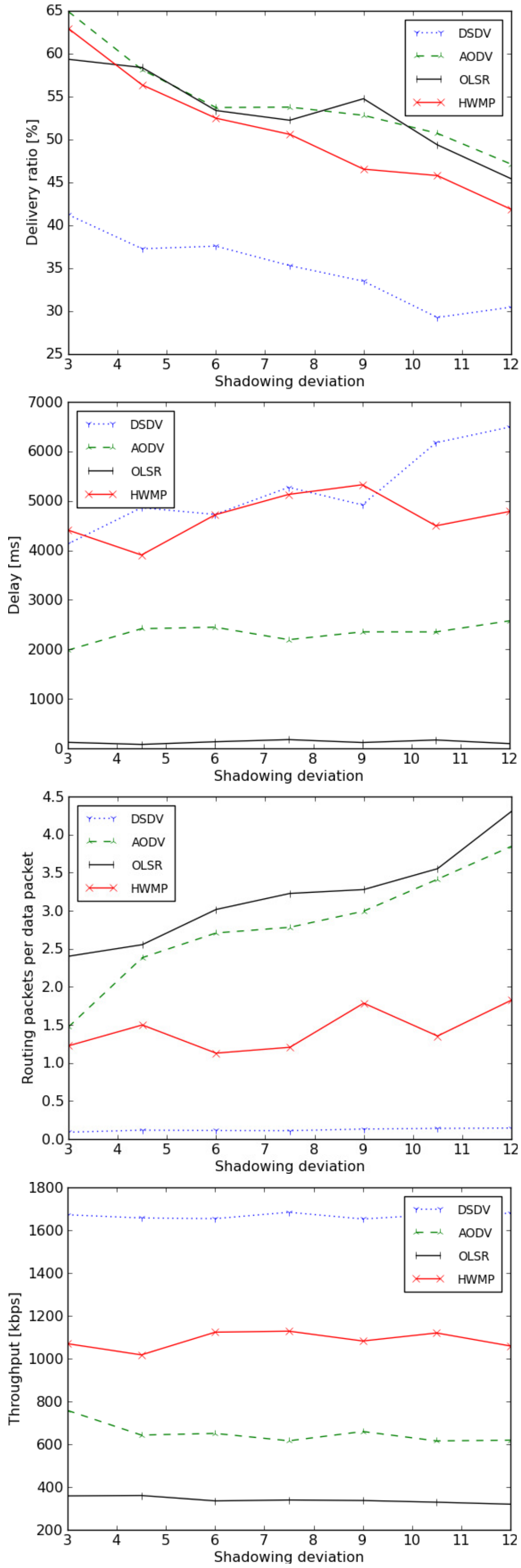


Figure 3. Delivery ratio, packet delay, routing load and system throughput in functions of the shadowing deviation.

### B. *Experiment 2. Impact of the path loss exponent*

Unlike the deviation, the path loss exponent does not introduce randomness imitating the presence of encountered obstacles, but affects the transmission range. Higher values of path loss exponent mean faster fading of transmitted signal power with growing distance from the source, and thus shorter transmitting, sensing and receiving ranges.

The plots in the first diagram (Fig. 4) representing the DR for individual routing protocols show very strong decreasing trend (lowering DR approximately to a third). DSDV is shown to be the least effective protocol in the whole experiment. The similarity in DR for AODV, OLSR and HWMP does not allow to select an unambiguous leader. All of them note a rather constant decrease of the DR summing up to the amounts from 53.7% to 56.8%.

The EED diagram (similarly to Fig. 3) shows significant differences between the investigated protocols. The EED function of the path loss exponent has a clearly visible, strong growing trend for HWMP – from 336ms up to nearly 7.4s – respectively for values 2 and 4.4 of the investigated parameter. The increase of EED for AODV routing protocol is also rather constant but considerably less intensive – from approximately 1s to over 3s. Whereas the DSDV plot shows a contradicting trend decreasing from 4.8s to 3.2s, which is a rather unexpected outcome. The other interesting finding concerns the OLSR plot. The EED is diminutive for values from 2 to 3.2 of path loss exponent. For higher values of this shadowing parameter OLSR protocol denotes a rapid EED growth of the order of several seconds.

The relatively smaller EEDs for low path loss exponent and their growth for more intensive signal fading can be logically explained. In perfect circumstances, when the wave propagation is undistorted and the signal power fades slowly, a lot of data is sent directly from its source to the destination. The decreasing range of the source and destination nodes disables the direct transmission and forces the source to send the packet through intermediate nodes. In this case the propagation and transfer times are multiplied by the number of intermediate hops and the total EED grows.

It is harder to explain the behavior of the DSDV protocol. The relatively low DR, especially for low values of path loss exponent, suggest that DSDV protocol, or at least its implementation for *ns* manages UDP traffic routing significantly less effectively than any other protocol.

The proactive character of this protocol is not to blame in this case. The true reason is most likely the way of disseminating routing information in the network. In case of DSDV it is performed by exchanging full routing tables with all of the currently detected one-hop neighbors. The lower the path loss exponent is, the further the nodes' range, and thus the bigger the one-hop neighborhood.

The big network load caused by large routing traffic, can influence the efficiency of data transmission. This effect is amplified by the fact that the routing messages are given higher priority than those carrying data.

The two remaining diagrams substantiate the assumptions made in previous paragraphs in this subsection. The RL is smallest for DSDV, from 0.05 for low values of path loss exponent, up to 0.8 for the strongest shadowing.

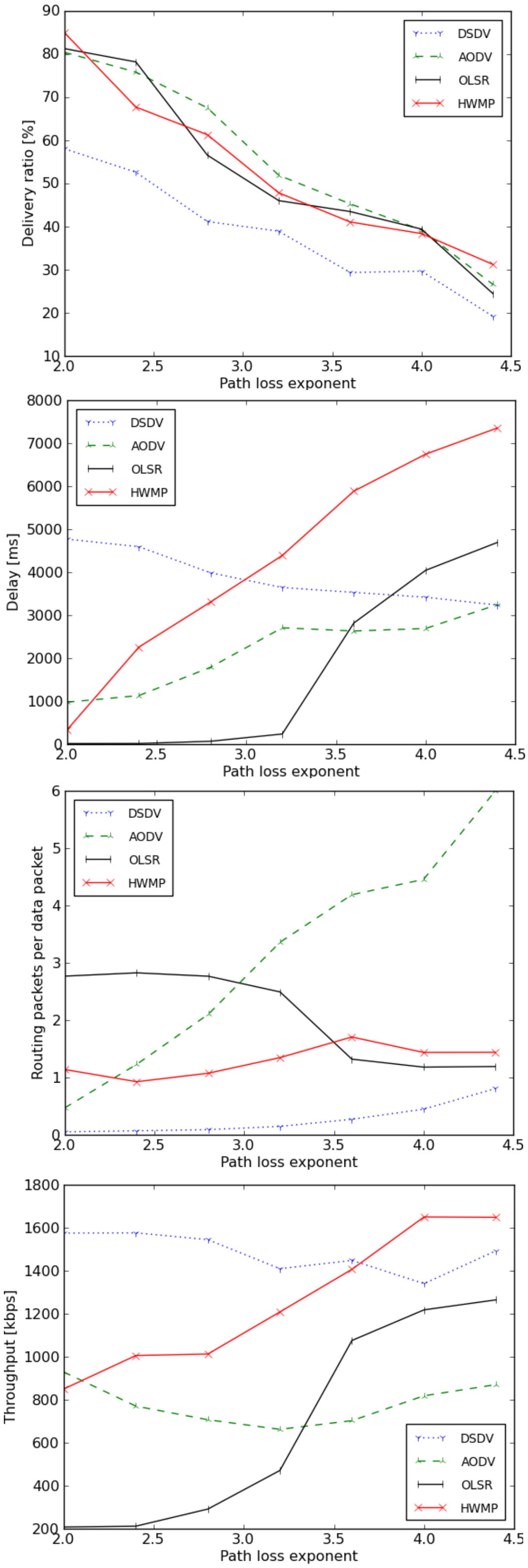


Figure 4. Delivery ratio, packet delay, routing load and system throughput in functions of the path loss exponent.

With more intensive shadowing less and less nodes belong to one-hop neighborhoods. For this reason a lot of broadcasted routing information needs to be forwarded, thus enlarging the RL. The HWMP protocol generates stable amount of approximately 0.9 to 1.4, in the extreme case 1.7, routing messages per one delivered UDP packet. The RL for AODV protocol grows most intensively with the path loss exponent. This happens because the decreasing nodes' range in mobile network causes more changes in topology, and consequently more frequent changes of the neighborhood, thus generating more on-demand routing information for this reactive routing protocol. The unexpected and fairly sudden decrease of RL for OLSR protocol seems somewhat anomalous and, confronted with other diagrams, gives an inkling of problems on implementation level, resulting in anomalies observed for more complex or particularly problematic scenarios.

The ST is the highest for the DSDV protocol, however intensively and almost constantly growing ST for HWMP reaches the same level of approximately 1600kbps for the high path loss exponent values – 4 and 4.4. The level of ST for AODV mostly reaches the values between 700 and 900kbps, which make it the most stable result.

This set of simulations has shown AODV as the most suitable protocol for network topology environments affected with strong shadowing. The DR obtained using AODV is in most cases the highest; the EED is the shortest, and the generated ST – the lowest. For less shadowed environments, like e.g., rural or indoor WMN applications, the OLSR protocol seems to be the right choice. However, in the face of the dubious accuracy of simulation outcomes for OLSR protocol a clear and irrefutable selection of the overall best routing protocol or protocols cannot be made.

## V. CONCLUSION AND FUTURE WORKS

This paper presented an investigation of WMN performance based on simulations with varying propagation conditions. The simulation results gave some direct remarks on the WMN performance, which may be used as support for decisions on the choice of a routing protocol or aid in the process of its design and development.

The experiment has shown that the performance, indicated by the predefined metrics, highly depends on the propagation conditions. The investigated protocols perform better in scenarios with low propagation parameter values.

The oldest of the investigated protocols - the proactive, distance vector routing protocol DSDV, performs very well only in terms of the RL. Regarding to the relatively low DR, long EED and high ST, DSDV efficiency is insufficient for use in modern WMNs even in good propagation conditions.

The main drawbacks of the hybrid protocol HWMP are the long EED and large ST. It is, however, still a well and reliably performing routing protocol. Its DR is considerably good. HWMP's strong side is the low and stable RL. Moreover, HWMP protocol, currently developed in IEEE 802.11s standard for WMN may prove to be more efficient, especially with parallel proactive and on-demand modes.

AODV – a reactive distance vector protocol, offers similar DR and low stable network load. The EED is considerably long but still acceptable. The downside is the sensibility to the propagation factors in case of RL. In the experiment with shadowing deviation AODV shows an intensive growth, but the generated RL is still adequate. In case of the path loss exponent experiment the result is the highest of all. Nonetheless, it is stable and robust, when influenced by changeable propagation.

The proactive, link state routing protocol OLSR has shown the best performance. Its EED is multiple times shorter than any other, the ST-indicated network load is low and the DR is among the highest. The drawback is the relatively high RL, which makes it prone to transmission collisions. These are, however, reduced by the MPR based topology information dissemination mechanism. These characteristics make the young OLSR a good routing protocol for areas with all propagation conditions.

In course of investigations several problems, which may create a perspective for future work, were encountered. These are, for example, the lacking compatibility of the routing protocol implementations as well as imprecision of the simulator modules' documentation.

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