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Efficiency of WLAN 802.11xx in the Multi-Hop Topology

Sławomir Kubal

***Abstract*—The article presents the research results of the performance of wireless multi-hop networks. The analysis of the decrease in performance of such networks depending on the number of hops was performed for three popular transmission techniques used in mesh networks: Hybrid Wireless Mesh Protocol (default routing protocol for 802.11s), Optimized Link State Routing Protocol and Wireless Distribution System. Based on the measurements results, mathematical models for the decreasing of network transmission parameters depending on the number of hops were developed.**

***Keywords*—802.11n, OLSR, 802.11s, HWMP, WDS**

I. Introduction

THE wireless networks are currently used in any environment for many applications. A typical topology of such network consists an access point AP providing services for terminals T connected to the network. The access point is usually wired to the core network, which makes possible to use services offered in the Internet. The single AP together with the terminals forms the basic service set BSS. A larger number of access points connected with each other form the extended service set ESS. Such typical topology is shown in Fig. 1.

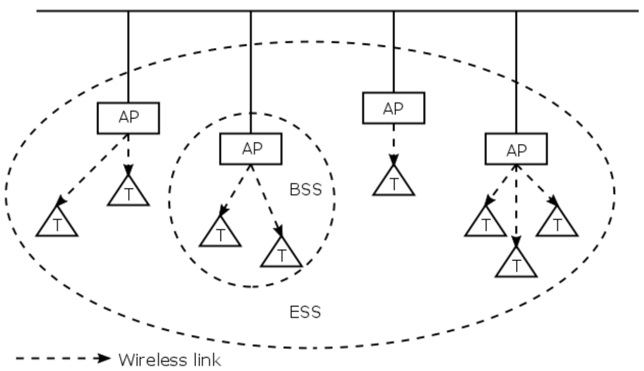

Fig. 1. Typical topology of wireless networks

The topology with access points wired to the core network has limitations associated with this wired connection. In many places it is not possible to build a wired network or it is unprofitable. An example of such environment is an underground mining excavation. Connecting points by wire in the mine, especially at the mining front, is inefficient and such connection is only present in a particular place near to the front. Therefore, it is possible to replace the wired connection with a wireless link constituting the core network. In this topology, access points connect with each other wirelessly and also provide services to terminals, usually using a different frequency band (than in the core network). Such topology is presented in Fig. 2. An example of the use of such topology in the mining environment is presented in [1].

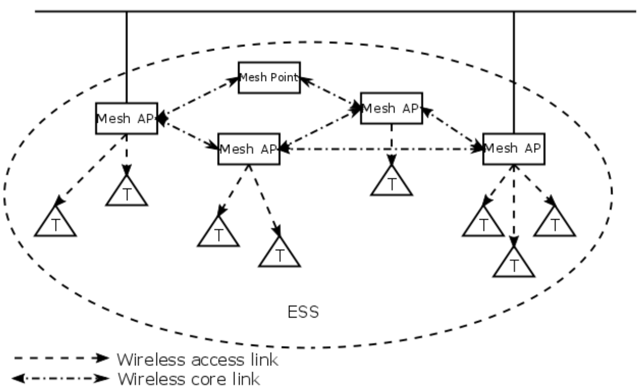

Fig. 2. Multi-hop topology of wireless networks

Appropriate techniques and protocols are used to implement the wireless core link. They include the Wireless Distribution System WDS or the 802.11s standard. The 802.11s describes the operation of a multi-hop mesh network. Mesh networks form one broadcast domain and connect with other networks using gates. Several classes of devices can be used in each mesh network:

- *Mesh Point* MP – sends packets beetwen other nodes,
- *Mesh Portal Point* MPP – mesh point, which is connected to the WAN network,
- *Mesh Acces Point* MAP – node, which sends packets between other devicess and additionaly provides access to services for terminals.

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Sławomir Kubal, Wroclaw University of Science and Technology, Telecommunication and Teleinformatics Department (e-mail: slawomir.kubal@pwr.edu.pl).

The 802.11s standard defines two types of mesh topologies: full mesh and partial mesh. In the first of them, each device connects to each other forming nodes. In the second one there is a different number of connections between devices. The use of mash topology has many advantages, such as: easy modification of network topology, energy saving, the ability to use in hard-to-reach areas. Unfortunately, the main disadvantage of this solution is the degradation of transmission parameters with each successive hop - the delay increases and the bandwidth decreases. Too many hops may result in the inability to provide services due to the low performance of such network

II. 802.11S STANDARD (HWMP)

IEEE 802.11s - it is one of the standards of the 802.11 group that specifies the medium access control MAC and the physical layer for wireless networks. 802.11s describes the operation of wireless networks operating in mash topology, while any standard of the 802.11x group can be used in the physical layer [2],[3]

Routing in 802.11s by default is based on the HWMP (Hybrid Wireless Mesh Protocol) protocol, which is based on the proactive tree method and RM-AODV (Radio Metric Ad-hoc On Demand Distance Vector) metric. In the proactive tree method, one node is the main node and it transmits the PREQ (path request) packet - a route request, which is send as the broadcast packet. The node that receives this packet sends the PREP (path reply) packet - the route response. This creates a proactive tree and the main node has a filled routing table.

RM-AODV is a routing metric designed for mobile and wireless ad-hoc networks. It depends on sending packets to nearby devices and finding the shortest path between them. Similarly, as in the proactive tree method, PREQ and PREP packets are sent, which also contain information about the cost of the connection. The distribution of PREQ and PREP packets in a typical mesh network is shown in Fig. 3.

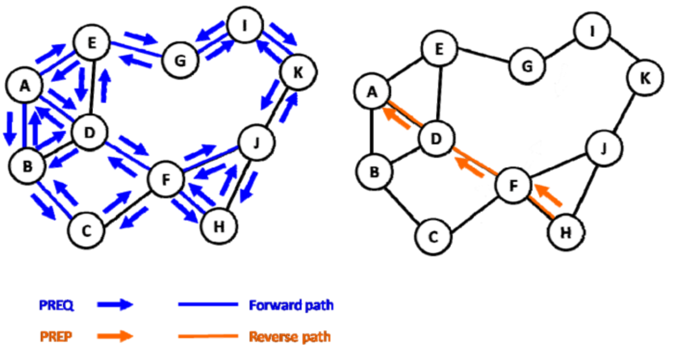

Fig.3. Operation of the HWMP protocol [4]

Assuming that node A is trying to find the path to node H, node A sends a PREQ message to nearby points - B, E and D. However, they are not the main target, so they cannot respond with a PREP message. Nodes B, E and D forward the PREQ message with the reduced TTL (Time To Live) parameter (packet lifetime) and they save the hop count and metrics. Than the PREQ packet is forwarded to nodes C, F and G. Nodes that had received this packet earlier may receive it again, e.g. A receives PREQ again from B, D and E, and D receives again PREQ from E and B. These nodes read the value of the TTL parameter. Based on its value they can determine, that it is a packet that had passed through another station and returned, so they reject it. The PREQ packet sent from E node is able to reach to the H node through stations G, I, K, J.

At the same time, nodes C and D will receive and forward the PREQ packet to the F node. This node receives PREQ three times - from nodes C, D and J. Assuming that F receive the first PREQ packet from node D when it receives PREQ from the C station, this frame would contain the same sequence number, but with a different number of hopes (the FDA route is shorter than the FCBA).

When the H node receives the PREQ packet, it responds with the PREP packet. The PREP is sent to the A node via the best path (the shortest path). If the station H receives a PREQ packet from the J node first, it can reply to it. However, when the H node receives the PREQ packet with a lower metric (from point F), it will learn a better route and the PREP packet will be forwarded through points F, D and A.

III. WIRELESS DISTRIBUTION SYSTEM

The wireless distribution system WDS is a system that allows to create a wireless connection between access points, based on 802.11x protocols. It allows to create a network with multiple access points without using a wired connection between them. This solution can cover a much larger area than a typical wired network. The operation of the WDS system is based on physical addresses MAC, therefore the whole system creates one broadcast domain. An important advantage of this mode is the keeping of the same MAC addresses in frames between access points. WDS can be built in two modes: using a wireless repeaters or a wireless bridges. In the first one, access points communicate with each other using WDS and provide access to services for wireless or wired client points. In the wireless bridge mode, the points communicate only with each other, without service providing for access terminals.

An important feature of the WDS system is the use of the same frequency channel for connections between nodes. If these nodes also provide a wireless access connection using the same network cards, access networks must also use the same channel. In the analyzed topology, the nodes were equipped with two network cards (one supports the WDS mode and the second one an access network), so the access and distribution networks could use different frequency bands and different channels. However, using the same channel for the distribution link between nodes degrades network performance parameters, especially when more devices are in the same network coverage area. An example of the WDS network consisting three nodes (two hops) is shown in the Fig. 3. Access points are connected with each other through the WDS system. Therefore, they do not require a wired connection in the distribution network and can be set up in a location without cable infrastructure.

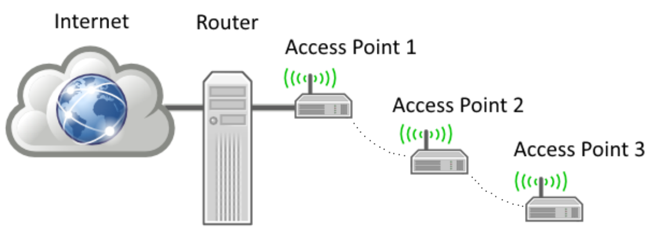

Fig.3. Typical topology of WDS [5]

IV. OLSR PROTOCOL

One of the most commonly used protocol in mesh networks is OLSR (Optimized Link State Routing Protocol). OLSR is a proactive protocol. Undoubtedly, its advantage is a full access to the route from the source to the destination at any time, even if there is no traffic at the moment. However for ensuring the immediate connections without any data loss, OLSR requires regular route updates between nodes. [6][8]

The operation of the OLSR protocol is based on sending of request packets for other devices in the network and building an association table based on the received replies. The particular node detects another and writes information about it in its topology table if there is a two-way connection between them. To do this, the node periodically sends 'HELLO' packets containing the addresses of all its neighbors. 'HELLO' messages are sent as a broadcast message to all directly connected nodes. This solution allows, that each node is able to know the number of neighbors (maximum distance is two hops). Each node stores in its neighbors table information about nodes distant by one hop and a list of nodes distant by two hops (they are neighbors of those distanced by one hop). Each entry in the neighbors table has its validity time, after which the connection is considered as inactive and then deleted.

One of the main tasks of the OLSR protocol is an effective detection of changes in network topology. For this purpose, OLSR uses a connection database. To fill this database, each node broadcasts Topology Control (TC) packets. TC messages are broadcasted at regular intervals, which, may be shortened as the network topology changes. On the other hand, Host and Network Association HNA messages inform how often a node, which is a sink to an external network in a mesh network, informs other devices that it provides access to the Internet (it is a default gateway in the network).

All devices in the network maintain a topology table, in which they store information received in TC messages. Routing tables are created based on information from the topology tables. The record in the topology table contains the address of the potential destination node, the address of the last hop (address of the TC packet author) and the corresponding sequence number. In addition, each record in the table has a validity time after which it is intended to be deleted. Comparison of OLSR and HWMP protocols is presented in [9].

V. MEASUREMENT SET-UP

The main purpose of the measurements was to examine the wireless network performance in terms of throughput and delay variability (jitter) parameters. The measurements were performed for a different number of devices in the network and with different network parameters: bands 2.4 GHz and 5 GHz and channel bandwidths of 20 MHz and 40 MHz (only for the 5GHz band). The measurements were performed for two, three and four intermediate devices according to the topology shown in Fig. 4.

The network has been configured in a chain topology. This topology allows to traffic control because only one packet route exists. In the mesh networks, routes are determined automatically. So if all devices are close to each other and each station is within range of all others, the last device in the topology connects to the first without the use of intermediate devices. The chain topology causes, that the traffic passes through subsequent devices, which allows to measure bandwidth and Jitter depending on the number of devices in the network.

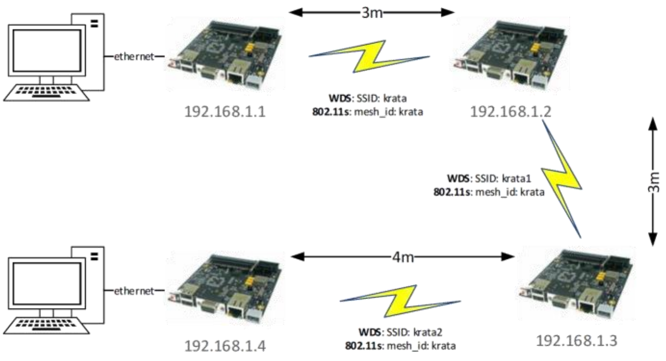

Fig.4. Measurements topology for three hops

Setting the chain topology for 802.11s require the using of static routing. Correctly configuration of the routing causes, that subsequent nodes connect only with their neighbors. For the WDS mode, there is no need to configure static routing, because individual nodes connect only to a neighbor belonging to the wireless network with the same SSID. As one can see in Fig. 4, individual wireless network between each point has different SSID. During the WDS configuration it is necessary to set which network are available for each node (e.g. the second node connects to the "krata" and "krata1" networks, it is not able to connect directly to the "krata2" network). In this way, packets are forwarded by subsequent nodes in the network. During measurements, the transmission speed and jitter were measured for each topology using the Iperf application. Three 60s repetitions were performed for each topology and each transmission mode and the average value was taken as the final measurement result.

The Laguna GW2387 microprocessor platform from Gateworks was used to build the network. These network processors can operate as wireless point-to-multipoint bridges, routers and gateways for 3G systems, pico WiMAX base stations. The GW2387 platform is based on the CNS3410 processor in the ARM11 architecture with a 300 MHz frequency. In addition it is equipped with interfaces: Micro SD cards, 2x Mini-PCI, Ethernet supporting 10BASE-T, 100BASE-TX and 1000BASE-T, 2x USB and 2x RS232. The devices have been loaded with the OpenWRT system (version 16.02) supporting 802.11s and WDS modes. The Laguna GW2387 platform is not equipped with a wireless card, therefore it was necessary to use external network cards. For this purpose, MikroTik RouterBOARD R52n-M cards were used, connected via the Mini-PCI interface. These cards support the 802.11a/b/g/n standards in two frequency bands: 2.4 GHz and 5 GHz. The R52n-M card enables data transmission up to 300Mbps using the 2x2 MIMO technique. The card also allows to set the transmission power to 23dBm, but during the measurements this value not exceed 20dBm, which is maximum value of EIRP acceptable in Poland. The measurements were performed for 2.4GHz and 5GHz frequency bands, therefore one was decided to use the 802.11n standard for communication between nodes. The properties of this standard compared to newer systems are presented among others in [10].

The test bed for the OLSR protocol was built based on Libelium Meshlium devices. Meshlium is a router based on Linux, whose main application is to operate as a gateway for Wireless Sensor Networks WSN. Additionally, it can be equipped in 6 different interfaces: WiFi 2.4GHz, WiFi 5GHz, 3G / GPRS, Bluetooth, Xbee and LoRa. Meshlium can be also integrated with the GPS module and operate with mobile applications using battery power supply or solar panels. Meshlium can operate as WiFi access point or WiFi Mesh device in 2.4 GHz and 5 GHz bands. The device is equipped with a processor clocked at 500MHz and 256MB RAM

The 802.11g standard was used to establish the connection between Meshlium devices. This standard has been implemented by the device manufacturer for communication in a mesh network. 802.11g operates in the ISM 2.4 GHz band and enables transmission with date rate up to 54Mb/s, while the real throughput (taking into account protocol overheads and access to the medium) in the network reaches up to about 35 Mb/s. For measurement purposes, a test set-up consisting of two, three or four Meshlium devices and two computers was built. The static routing was set on all intermediate devices to ensure a specific transmission route in the chain topology from one computer to another.

VI. Measurements results

Measurements of wireless network performance for the OLSR protocol, as was mentioned, were performed using the 802.11g standard (in the physical layer) for two, three and four intermediate devices (respectively one, two and three hops). In addition, the measurements were carried out for two different OLSR modes: fixed, in which the devices do not change their position, and mobile. The following parameters of the OLSR protocol were set for the fixed mode: Hello Interval = 5 s, TC Interval = 5 s and HNA Interval = 5 s, while for the mobile mode respectively: Hello Interval = 1 s, TC Interval = 1 s and HNA Interval = 2 s. The measurement results are shown in Fig. 5 and Fig. 6.

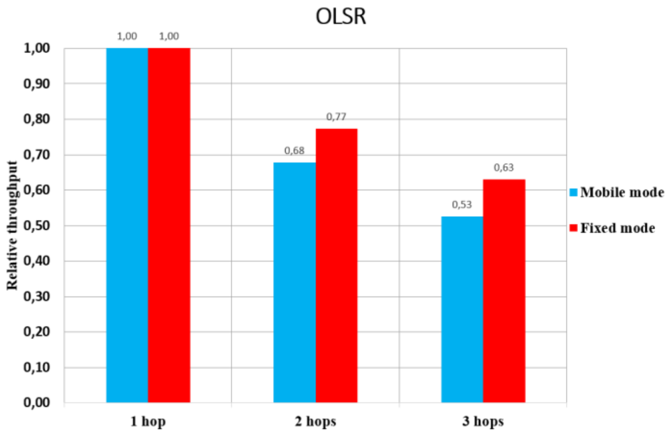

Fig.5. Measured relative throughput for the OLSR protocol

As one can see, the results for the OLSR protocol are quite good, the decreasing of transmission parameters is less than for other techniques. It is worth noting that better measurements results were obtained for the fixed mode than for the mobile mode. It is directly related to the number of additional packets sent by the OLSR protocol. For the fixed mode these packets are sent less often, therefore their number is smaller in the particular measurement time. It should be also mentioned, that for the used chain topology (with no changes in the topology) the operation of the OLSR protocol is limited in relation to the mesh topology. If there are no topology changes, the OLSR protocol does not send additional packets that could also degrade network performance.

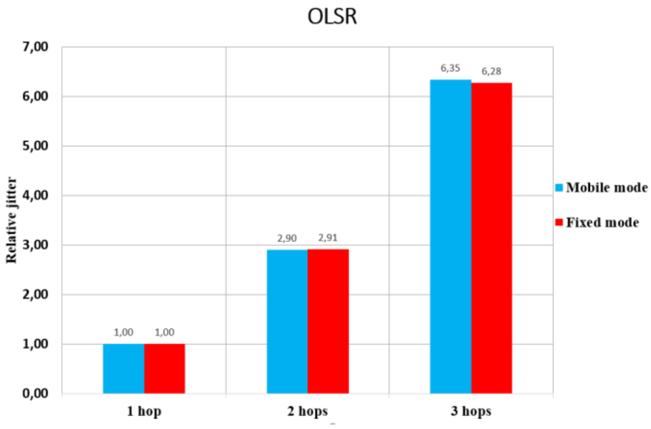

Fig.6. Measured relative jitter for the OLSR protocol

The measurements of multi-hop network performance based on WDS were performed, as for the OLSR protocol, for two, three and four intermediate devices. To eliminate the impact of the 802.11n standard used in the physical layer, measurements were carried out for three different modes of the physical layer: 2.4 GHz band and 20 MHz channel, and 5GHz band for two channel bandwidths 20MHz and 40MHz. The results of throughput and jitter measurements in a multi-hop network based on WDS in relation to the one-hop case are presented in Fig. 7 and Fig. 8.

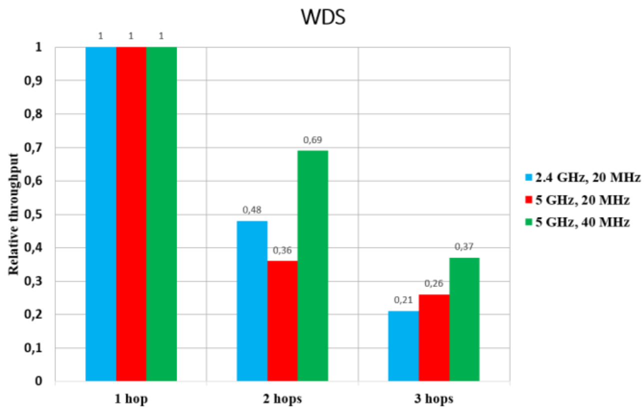

Fig.7. Measured relative throughput for the WDS system

Analyzing the measurement results achieved for the WDS technique, one can notice a clear increase in jitter value for increasing the number of devices in the network. For WDS technique each node is connected to two different wireless networks (with two different SSIDs). A significant increase in jitter in a multi-hop network is most likely related to the access to the medium (twice for the each node), which is based on the Carrier Sense Multiple Access Colision Aviodance CSMA/CA protocol. It significantly increases the time parameters of the transmission in the network, also causing significant decreasing of transmission rate.

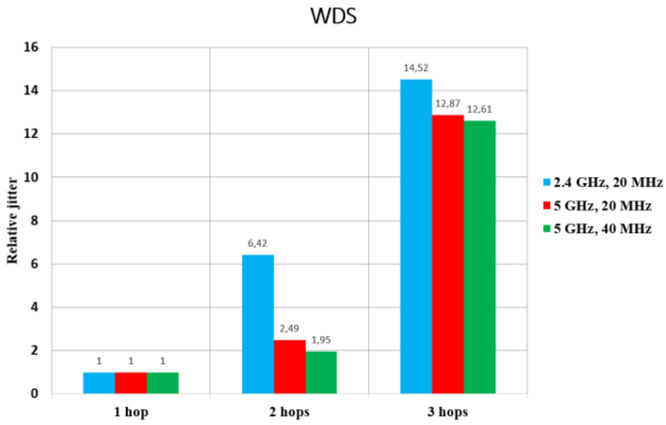

Fig.8. Measured relative jitter for the WDS system

The measurement results for the default routing protocol in 802.11s networks (HWMP) are shown in Fig. 9 and Fig. 10. Similarly to the WDS, measurements were performed for three different modes of the 802.11n standard for the chain topology consisting two, three and four intermediate devices.

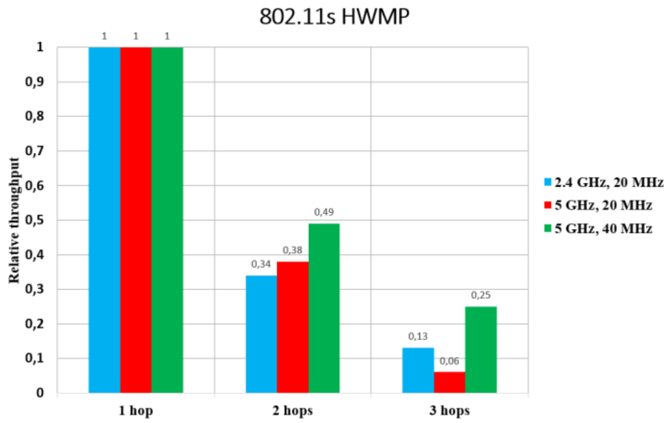

Fig.9. Measured relative throughput for the HWMP protocol

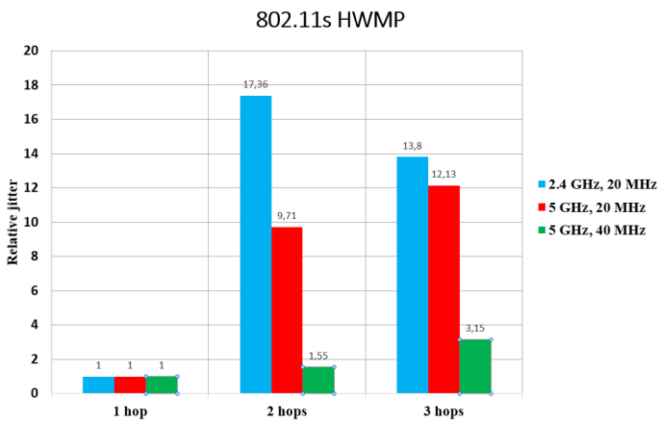

Fig.10. Measured relative jitter for the HWMP protocol

In this case, it was necessary to set the static routing in the network. The results obtained for this protocol for particular modes in the physical layer differ significantly from each other. For the 5 GHz/40 MHz case, jitter values were significantly lower than for the other modes (also for other transmission techniques). This result was obtained with many repetitions of measurements, but it can not be clearly explained what was the reason for this. An anomaly obtained for the jitter measurement for two hops (the value for two hops is greater than for three) may be caused by a temporary lack of communication in the network.

The values measured for a particular solution have been averaged to get the final results of throughput decreasing and jitter increasing. The results for all three transmission techniques are summarized in Figures 11 and 12. As one can see, the best results (the smallest decrease in throughput and the least delay increasing) were achieved for the OLSR protocol. Unfortunately, due to the insufficient memory capacity of Laguna devices, the author was not able to install the OLSR protocol on them. However, the performance of Meshlium devices is less than GW2387 devices, which also confirms the superiority of the OLSR protocol over the other two solutions.

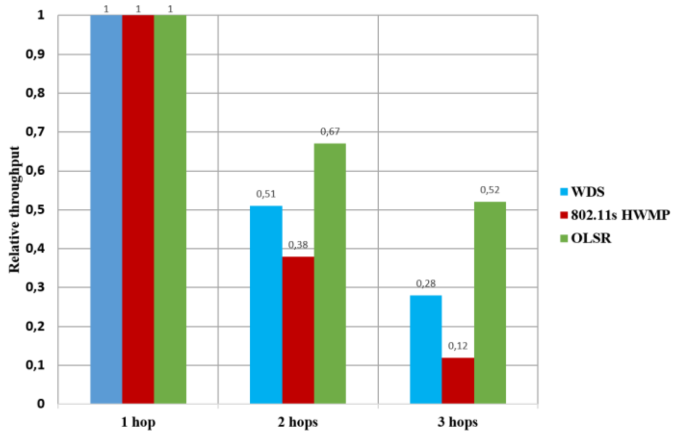

Fig.11. Comparison of relative throughput for all techniques

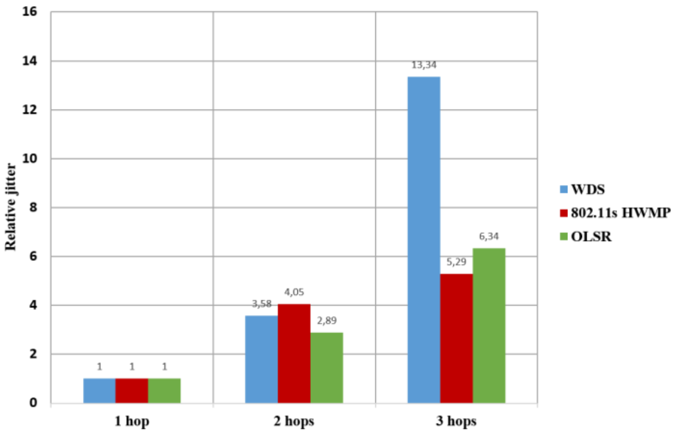

Fig.12. Comparison of relative jitter for all techniques

VII. Mathematical Model

Based on the measurements results, a mathematical model was developed for the throughput decreasing and jitter increasing for the multi-hop network depending on the number of hops. The model describing the increasing of the delay variation in the network relative to the single-hop network describes the relationship (1):

$$Rel\_jit = 0.863.* n^{2.066} \quad (1)$$

The coefficient of determination R^2 and the sum of squares error SSE were determined for the developed model. The determination coefficient R^2 is a matching measure of the values obtained with the regression model to the real values obtained during the measurements. The coefficient of determination determines what part of the variability of the dependent variable is explained by the regression function for this variable. The value of the R^2 coefficient takes values from 0 to 1. The closer to the unity the better description of the analyzed phenomenon by developed model. SSE is a measure of the deviation from the real value that we obtain using the model. In the ideal case, the SEE is equal to 0, i.e. the developed model accurately describes the analyzed phenomenon. [11] For the developed model of relative variability of jitter, the following values of the coefficient of determination and error SSE were obtained: $R^2 = 0.999$, SSE = 0.027

Similarly to the relative jitter, a model for changing the throughput in the network depending on the number of hops was developed. The decreasing of the network bandwidth in relative to one-hop connection describes the relationship (2):

$$Rel\_th = 1.214 * n^{-0.748} - 0.189 \quad (2)$$

The same parameters describing the model accuracy with the analyzed phenomenon were determined for the developed model. For throughput, the values of the coefficient of determination and SSE error are respectively: $R^2 = 0.954$, SSE = 0.011.

It should be noted that the developed models keeps the calculated values of the R^2 and SSE parameters for the number of hops from 2 to 10. In real networks, there should be no more than 10 hops. With such a hops number, the degradation of transmission parameters is very large, which practically causes that data transmission with acceptable level is impossible. Figures 12 and 13 present graphs showing the relative decrease in throughput and the increase in delay variation for a multi-hop network, These figures present graphically developed mathematical models.

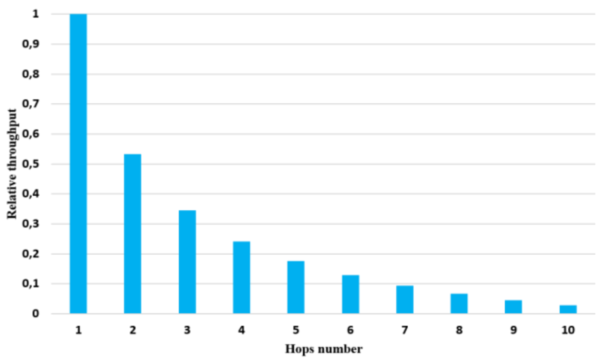

Fig.12. Calculated relative throughput

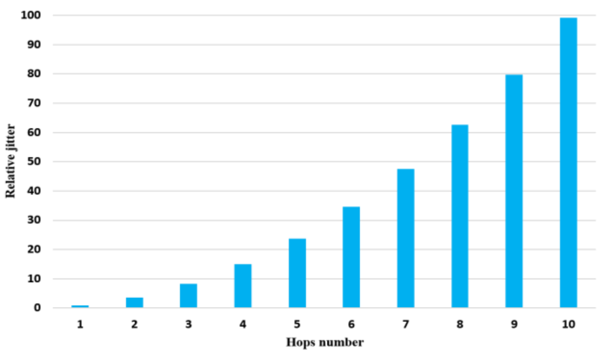

Fig.13. Calculated relative jitter

Conclusion

Increasing the number of hops in the multi-hop wireless network causes decreasing of transmission parameters of such networks. It is rather obvious statement. But building such networks one should be aware that each additional hop causes decreasing of network throughput almost by half. Also the value of jitter very fast grows for the greater number of nodes. Therefore using multi-hop networks the maximum number of hops should not exceed five or six, especially when in this network the real-time services (e.g. voice transmission) are provided.

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