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IMPROVING DATA TRANSMISSION EFFICIENCY IN WIRELESS AD-HOC NETWORK

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF A DOCTOR OF ENGENEERING SCIENCES

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council ”RTU P-08” on June 30, 2016 at the Faculty of Electronics and Telecommunications of Riga Technical University, Azenes Street 12, Room 2-38.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences, is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to other scientific degree.

Lauris Cikovskis . . . . (Signature)

Date: . . . .

The Doctoral Thesis has been written in the Latvian language. It contains an Introduction, 5 Chapters, Conclusion, Bibliography, 6 appendices, 65 figures and illustrations, the total number of pages is 190. The Bibliography contains 126 titles.

Contents

Acronyms

AODV	Ad-hoc Ondemand Distance Vector Routing.
AODVM	Ad-hoc On-demand Distance Vector Multipath.
CPU	Central Procesor Unit.
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance.
DSP	Digital Signal Processing.
HPC	High Performance Computing.
LC	Leyared Coding.
MAC	Media Access Control.
MATLAB DCS	Matlab Distributed Computing Server.
MDC	Multiple Description Coding.
MIMO	Multiple-Input and Multiple-Output.
OLSR	Optimized Link State Routing.
OSI model	Open Systems Interconnection model.
PCS	Physical Carrier Sense.
RTS/CTS	Request To Send/Clear To Send handshake.
SINR	Signal to Interference plus Noise Ratio.
SM	Spatial Multiplexing.
SMR	Split Multipath Routing.
WLAN	Wireless Local Area Network.

GENERAL DESCRIPTION OF THE THESIS

Significance of the Research

In the recent years, the number of mobile devices which use data transmission services has been increasing rapidly. At the same time performance of the devices is also improving, e.g. Exynos 7 system-on-chip which is widely used in smart phones has two quad-core ARMv8 processors. Such devices have better functionality and allow intensive data processing and transmission tasks, e.g. high resolution video streaming, cloud computing services, etc. They are intended to be always on-line and that requires ubiquitous availability of services. As a result, the growing data traffic is becoming a challenge for cellular network operators. Figure 1 shows a forecast about mobile data traffic growth during the next few years, the biggest part of which will be video data. Video transmission has the highest requirements for quality of service therefore the research done in the thesis is oriented to this application.

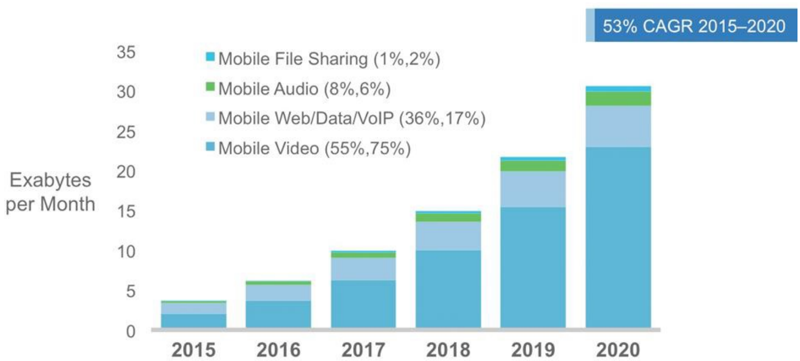


Figure 1: Cisco Systems Inc. forecasts about the increase of data amount in mobile networks [1]

Topical are the research directions which will help to offload traffic from cellular networks as well as expand the network coverage to uncovered places. In hybrid network solutions two users who are close to each other can exchange with data directly without an involvement of base station (device-to-device communication). Such option is planned for the next generation 5G mobile networks [2]. Wireless ad-hoc network also relies on device-to-device communication as well as provides multi-hop transmission if direct connection is not possible, self-organization and other features.

Ad-hoc network can be a part of hybrid network or function fully independently and provide communication in places without an existing infrastructure. However there are several problems typical of IEEE 802.11 standard ad-hoc network: limited capacity and unpredictability. Network capacity is limited by wireless links which are subject to interference. Network capacity decreases with the increasing of the number of hops. Unpredictability is caused by mobility of the devices which may lead to packet loss and delays.

Multi-path transmission can increase capacity of ad-hoc network as well as decrease probability of path breakage which is important for video transmission. Although creation of multiple paths requires an involvement of more nodes, number and density of mobile devices keep increasing that makes the scenario possible. There are many studies on effective path discovery but the selection of suitable paths for video transmission is analysed less which is emphasized in the thesis. When data stream is split over several paths one must take into account higher interference that decreases multi-path transmission potential to increase capacity.

To improve efficiency of multi-path transmission some techniques should be used to decrease interference. One which is studied in the thesis is smart antenna. It may decrease interference between ad-hoc network nodes with the help of beamforming and also increase data rate by using technology. Since there is a tendency in wireless communication to switch to higher carrier frequencies application of such antennas in mobile devices will increase. Improvement of digital signal processing capabilities will also foster it. Smart antennas are widely used in traditional wireless communication in base stations (also WiFi access points [3]) but are not studied sufficiently for ad-hoc networks and multi-path transmission. Optimal path selection may provide additional benefit to smart antenna which is also studied in the thesis.

Although the research done in the thesis is mainly focused on IEEE802.11 standard ad-hoc network, the results can refer also to other types of ad-hoc networks carrier sense multiple access method used, e.g. sensor networks. The interference problem covered in the work is topical also for WiFi networks the number of which is still permanently increasing. Also it should be admitted that increase of data transmission rate is not intended only for entertainment field which may have a negative impact on human. Ensuring video transmission in wireless network is important in the fields like emergency services, medicine and education.

Aim and Objectives

The aim of the thesis is to improve data transmission efficiency in wireless ad-hoc network by using multi-path transmission and techniques to cancel interference. To achieve the aim the following objectives have been stated:

1. Perform analysis of the factors limiting IEEE 802.11 standard ad-hoc network capacity and summarise possible solutions.
2. Develop an algorithm for efficient video transmission which takes into account network parameters.
3. Evaluate the impact of interference on network throughput and find solutions to decrease interference.
4. Review the existing methods for estimating capacity of multiple paths, adapt the chosen method for the research.
5. Elaborate the ad-hoc network simulation tool in MATLAB environment which is based on the method chosen in task 4 and additive interference model.
6. Conduct computer simulations to evaluate efficiency of interference cancellation methods.
7. Elaborate guidelines for choosing an effective solution for data transmission in ad-hoc network.

The subject of the research is IEEE 802.11 standard ad-hoc network for video transmission applications. The object of the research is network capacity, interference impact on it and techniques to cancel interference when video data stream is transmitted over multiple paths.

Research Methods

The research on multi-path video transmission and elaboration of algorithm is based on the analysis of related research presented in scientific papers. Additionally literature is analysed to study interference cancellation methods and identify unresolved issues.

Impact of inter-path interference has been investigated experimentally. For this purpose

IEEE 802.11g/n standard ad-hoc network testbed has been created. Since the capabilities of experimental research are limited Network simulator NS-2 [4] has also been used.

Interference cancellation techniques have been evaluated with numerical analysis by measuring how much they can improve path capacity. The method to estimate path capacity is based on an analytical maximum flow problem which is solved numerically with linear optimisation [5], [6]. In the thesis the method has been improved with CSMA/CA protocol simulation model which includes additive physical interference, and additional constrains for optimisation problem to describe better multi-paths transmission. The method has been implemented in MathWorks MATLAB [7] as a complete network simulation tool.

Statistical methods have been widely used in the analysis. To obtain the results independent on network topology statistically average path capacity is estimated with the help of Monte-carlo simulation. The number of random scenarios must be high enough to observe statistically significant differences in the results. To decrease simulation time the parallel computations on High Performance Computing (HPC) cluster have been performed.

The Main Results

Multi-path transmission together with the techniques for interference decreasing improves data transmission efficiency in wireless ad-hoc network.

- Experimental evaluation done in the wireless ad-hoc network testbed proves that inter-path interference has essential influence on data rate: in the case of high interference level multi-path transmission does not increase aggregated path capacity.
- The results of ad-hoc network analysis have been schematically summarized in network parameter interrelationship model. The model visually links the factors that influence network with metrics important for video transmission. Similar research considering such great variety of parameters in such perspective cannot be found.
- Data transmission efficiency is studied with the help of maximal flow problem solving method. In contrast to other works the method has been used with additive interference model as hybrid method. Additive model provides more accurate multi-path capacity evaluation if compared to more often used distance based interference model.
- On the basis of hybrid method and parameter interrelationship model the network simulation tool has been elaborated in Mathworks Matlab environment which can be effectively used for analysis of many random scenarios. The tool includes model for SMR routing protocol which has been improved to provide paths sets with 2 – 3 times higher diversity if compared to original SMR or AODV protocol.
- Data transmission efficiency is improved when multi-path transmission is used with techniques for interference decreasing.
  - Splitting data stream over multiple paths increases data rate up to 50 % if critical boundary of distance between source and destination is taken into account (5 hops in the thesis). It influences both optimal number of paths and selection criteria used.
  - When optimal path selection is combined with the application of smart antennas, maximal data rate improvement is achieved. Several smart antenna types have been compared in multi-path transmission including MIMO for the first time. It has been concluded that adaptive antenna array with single spatial stream most effectively cancels interference and doubles capacity when the number of paths is increased.
  - As a summary of the results the guidelines have been prepared helping to select optimal paths considering antenna type and network parameters.

Thesis Statements to be Defended

It is defended, that:

1. extended ad-hoc network interrelationship model which visualises influences between important factors and parameters ensures an effective elaboration of algorithms and simulation tools;
2. the hybrid method which combines maximum flow method with the elaborated in the thesis Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol simulation model including additive interference is an effective solution to estimate capacity of multiple paths;
3. to achieve data rate increase by splitting flow over multiple paths a critical boundary of the distance between source and destination exists;
4. when data flow is split over multiple paths the maximal increase of data rate is provided by adaptive antenna array with single spatial data stream which cancels mutual interference according to the number of degrees of freedom.

Practical Application of the Results

- The model of ad-hoc network parameter interrelationships demonstrates logical steps to estimate important path metrics. It can help in the development of algorithms and software for such tasks as it has been shown in the thesis by elaborating network simulation tool.
- The improved analytical method and elaborated MATLAB tool is applicable for research of transmission efficiency in ad-hoc networks. Program code is public and available in GitHub repository which allows everyone to continue work on it. The tool has been also piloted in HPC cluster of Riga Technical University where MATLAB DCS module has been integrated for this purpose.
- The results of the thesis have been summarized in practical guidelines to improve data transmission efficiency in ad-hoc network. Guidelines can be used in routing protocols for decision making algorithms.
- Within scope of the thesis IEEE 802.11g/n standard ad-hoc network testbed has been created having been demonstrated in study courses related to electrical engineering as well as used in several Master and Bachelor Thesis.

Approbation

Conferences. The results and the research related to the thesis have been presented at the following conferences:

1. Advances in Wireless and Optical Communications (RTUWO), Riga, Latvia, November 5–6, 2015;
2. The 2nd Joint IEEE Lithuania and Latvia Sections Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE'14), Vilnius, Lithuania, November 28–29, 2014;
3. RTU 55th international scientific conference, section „Electronics", Riga, Latvia, 14–17 October, 2014;
4. 21th Telecommunications Forum (TELFOR), Belgrade, Serbia, 26–28 November, 2013;
5. 20th Telecommunications Forum (TELFOR), Belgrade, Serbia, 20–22 November, 2012;
6. 1st Baltic HPC and Cloud computing conference, Riga, Latvia, 10–11 September, 2013;
7. 2nd International Conference on Digital Information Processing and Communications, Klaipeda, Lithuania, 10–12 July, 2012;

8. RTU 52th international scientific conference, section „Electronics”, Riga, Latvia, 13–16 October, 2011;
9. The 15th International Conference Electronics‘2011, Kaunas, Lithuania, 17–19 May, 2011;
10. RTU 50th international scientific conference, section „Electronics”, Riga, Latvia, 15–16 October 2009;
11. Balticgrid II 2nd All-Hands Meeting, Riga, Latvia, 12–14 May, 2009.

Scientific publications. The results of the thesis have been reflected in the following publications:

1. Cikovskis L., Slaidins I. Path Selection Criteria for Multi-path Routing in Wireless Ad-hoc Network.// Advances in Wireless and Optical Communications (RTUWO2015), – Rīga, 2015. – pp. 64–67. (**Scopus, IEEE xplore**)
2. Cikovskis L. Inter-path Interference Cancelation in Wireless Ad-hoc Networks Using Smart Antennas.// Proceedings of IEEE 2nd Workshop on Information, Electronic and Electrical Engineering (AIEEE). – Viļņa:IEEE, 2014. – pp. 1–6. (**IEEE xplore**)
3. Cikovskis L. Method for analyses of data transmission over multiple paths in wireless ad-hoc networks.// Proceedings of 21th Telecommunications Forum (TELFOR). – Belgrade:IEEE, 2013. – pp. 133–136. (**Scopus, IEEE xplore**)
4. Cikovskis L., Slaidins.I, Vdovins S. On optimal video transmission over multiple paths in wireless ad-hoc networks. //Proceedings of 20th Telecommunications Forum (TELFOR). – Belgrade: IEEE,2013.– pp. 319–322. (**Scopus, IEEE xplore, EBSCO**)
5. Cikovskis L., Slaidins I. Analysis of wireless ad-hoc network parameters for efficient multipath video transmission.// Second International Conference on digital Information Processing and Communications (ICDIPC). – Klaipeda:IEEE, 2012. – pp. 16–21. (**Scopus, IEEE xplore, EBSCO**)
6. Cikovskis L., Slaidins I. Impact of physical carrier sense range on network throughput in wireless ad-hoc networks.// Scientific Journal of RTU. 7. series, Telecommunications and Electronics. – Riga:RTU, 2011. – no.11. – pp. 16–21. (**EBSCO**)
7. Cikovskis L., Vdovins S., Slaidins I. Multipath routing with adaptive carrier sense for video applications in wireless ad-hoc networks.// Elektronika ir Elektrotechnika. Kaunas, 2011. – no.6. – pp. 37–42. (**Scopus**)
8. Cikovskis L., Kulins J., Vdovins S., Slaidins I., Zhuga B. Ad-hoc and wireless mesh networks for mobile peer-to-peer collaboration.//Scientific Journal of RTU. Telecommunications and Electronics. – Riga:RTU, 2009. – no.9. – pp. 50–57. (**EBSCO**).

Projects. The results of the thesis have been used in the following research projects:

1. “Innovative signal processing technologies for smart and effective electronic system development”, State research program project no.2, 2010–2014;
2. “New electronic communication technologies”, State research program project no.5, 2008–2009.

Also the author has received support from “eInfranet” project financed by the European Commission, in 2010–2013.

Structure of the Thesis

The thesis consists of general description (introduction), 5 main chapters, conclusions, the list of references and 6 appendices.

Chapter 1 is a general introduction to ad-hoc networks and data transmission related problems. Literature analysis has been done on solutions increasing network capacity which are improved later in the thesis.

Chapter 2 is devoted to multi-path video transmission and analysis of ad-hoc network parameters in the process. On the basis of existing solutions and analyses of connections between ad-hoc network parameters, a schematic interrelationship model is created. The model demonstrates interference impact on multi-path transmission efficiency.

In Chapter 3 solutions to reduce interference are analysed: selection of a suitable paths and smart antennas. The chapter includes theoretical background of smart antenna technology and their application in ad-hoc networks. Unresolved issues have been identified and research objectives clarified.

In Chapter 4 a method and simulation tool is elaborated for capacity estimation of multiple paths. Accuracy of the results is tested and solutions to decrease simulation time are sought.

In Chapter 5 computer simulation is used to evaluate effectiveness of interference reduction techniques. Studies are finalized with guidelines for selecting suitable path set according to antenna type and network parameters.

Totally the work comprises 190 pages, 65 figures, 10 tables and 126 references.

SUMMARY OF THE THESIS CHAPTERS

1. Data Transmission in Ad-hoc Network

Wireless ad-hoc network (further ad-hoc network) is a group of mobile devices (nodes) which can self-organize and self-configure to create a network. In contrast to a traditional wireless network, communication between the nodes is direct without central control (device-to-device). For the research of this thesis only packet communication using IEEE 802.11g/n standard devices and protocols are considered which are also used in Wireless Local Area Network (WLAN).

Functionality of ad-hoc network depends on the network layer of Open Systems Interconnection model (OSI model) which ensures connectivity if two nodes cannot reach each other directly because of limited transmission range. Data packets are sent over multiple hops through other network nodes functioning as routers (also called relays). To ensure path for data forwarding a routing protocol is required. The protocol must create stable path, immediately react to the changes in network topology for which the protocols used in wired networks are not suitable. Two main classes of routing protocols for ad-hoc networks are proactive and reactive. When proactive protocol is used each node keeps routing information on how to reach any other node irrespective whether it will be used. Reactive protocol crates routes on demand only when it is needed.

Classical application of ad-hoc networks is to provide communication for specific task in a place without existing network infrastructure. Ad-hoc network can be used to exchange with data between two devices, provide data exchange among participants of a conference or communication between rescuers in catastrophe area, etc. However, ad-hoc network for general purpose in practice is not feasible [8]. It is suggested to narrow research to several pragmatic applications such as hybrid networks and specialized ad-hoc networks.

In the recent years, special attention is paid to different hybrid network solutions where ad-hoc network is combined with other network types, e.g. wireless mesh network or mobile cellular network. Next generation 5G mobile networks will include ad-hoc network functionality to enable direct data exchange between users without involvement of base station [2]. Specialized ad-hoc networks are created to meet specific user needs, e.g. vehicular ad-hoc network (VANET), which is used for inter vehicular communication, or wireless sensor network (WSN) which is used to gather data from sensors, as well as network which is used for virtual collaboration with video conferencing.

Video transmission puts the highest requirements on network because large amount of data is transmitted (for 720p ”HD” H.264 compressed video is 4 Mb/s), it is sensitive to packet losses and it requires low delays. At the same time it is a very topical application because of increasing amount of video data in wireless networks (Figure 1). Video transmission is used as a target application of the research.

Ad-hoc networks are based on IEEE 802.11 wireless network standard primary intended for WLAN. This is one of the reasons why protocols are not well suited for a decentralized, multi-hop network with dynamic and unpredictable nature [9], [10]. Consequently data rate is unstable and insufficient which is not suitable for video transmission. Other problem is mutual interference between nodes that degrades data rate. IEEE standard uses two bands at 2.4 GHz and 5 GHz frequency which are further divided in fixed-width channels (20 MHz or 40 MHz).

Participants of the same network (same SSID) share one channel causing interference.

Access to the channel is controlled by CSMA/CA Media Access Control (MAC) protocol. Although CSMA/CA is considered to be suitable for decentralized infrastructure it has also several drawbacks. First, nearby nodes (located in each other carrier sense range) is not allowed to transmit simultaneously therefore the packets are waiting in the queue for an idle channel state. For intensive data flow it decreases average data rate or may even cause network congestion. Secondly, the nodes outside each other carrier sense range are allowed to transmit but since they use the same radio channel radio interference exists. It worsens the conditions for packet reception and decreases link capacity or may even cause packet collision. In multi-hop transmission the interference level is higher because mutually competing links are close. Consequently data rate falls with the increasing of the number of hops.

Some solutions to increase network capacity have been analysed in the chapter. The investigation showed that the approach should be ”vertical” when several OSI layers are improved with the help of cross-layer collaboration. Development of new lower layer standards is not useful because ad-hoc network is based on widely spread IEEE 802.11 devices. The main input should be in the improvement of existing protocols and increasing efficiency of their application. More opportunities are to improve OSI network and application layer.

Multi-path transmission is one of the solutions emphasized in the chapter because it requires less changes to IEEE 802.11 standard. In multi-path transmission several paths between source and destination are used (Figure 1.1) with several benefits: fault-tolerance, load balancing and increase of aggregated capacity. These can improve network capability to transmit video data [11], [12]. The topic which has been investigated extensively is effective path discovery (e.g. in overview [13]) but less effort has been devoted to path selection for video transmission.

Although network capacity cannot be increased directly through application layer it can

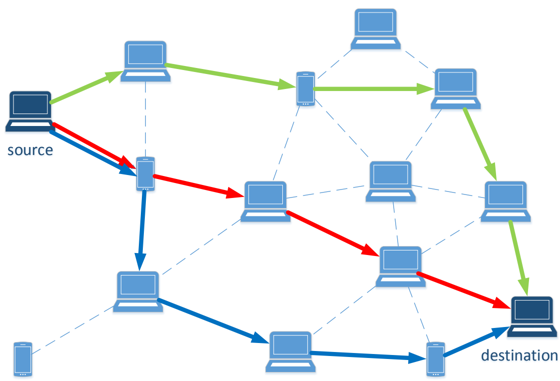


Figure 1.1: Data transmission over multiple paths simultaneously

be influenced for example by preventively avoiding network congestion. If video transmission is considered as an application, improvements can be reached in video coding and transmission techniques. To send video data over several paths, different coding methods e.g. Multiple Description Coding (MDC) un Leyared Coding (LC) [11] and routing protocols can be used. It is important to select optimal set of parameters for ad-hoc network which is still an unresolved issue. Therefore an algorithm effectively applying existing methods and taking into consideration also network capabilities should be developed. Ad-hoc network functioning and parameters during video transmission are analysed in the next chapter.

Smart antennas have a potential to decrease interference between the nodes [14] and they are also used in infrastructure networks like WLAN [3]. So far their application in ad-hoc network has been limited therefore in the thesis an additional research has been made.

2. Analysis of Ad-hoc Network Interrelationships

Video can be sent over multiple paths to improve transmission efficiency in ad-hoc network. Improvements are achieved by means of balancing load and aggregating capacity of individual paths. To get full advantage of multiple paths the evaluation of network performance and selection of optimal video coding and transmission parameters are of high importance otherwise video quality may degrade. In this chapter on the basis of existing solutions and analyses of ad-hoc network factors and parameters, the network interrelationship model has been developed.

Initially existing solutions for video transmission in ad-hoc network are analysed. The analysis reveals that no common approach on selecting optimal parameters suits ad-hoc network in general. However several basic principles are to be followed when coding method, number of streams, bit rate and routing protocol are selected:

- coding method (LC or MDC) is selected considering packet loss and delay requirements;
- optimal number of streams depends on coding method and number of paths found: for MDC method more than one stream and for LC method 3 streams;
- bit rate for a stream is determined by path capacity which must not be exceeded;
- stream allocation to paths depends on packet loss and delay (important for LC);
- for real time video proactive routing protocol should be chosen, for steaming – reactive.

For effective usage of multiple paths, network parameters should be evaluated each time video data is prepared for sending. Taking into account the principles discussed above, coding parameters are selected.

The results of the analysis have been used to elaborate conceptual algorithm for video coding which is published in [15]. The algorithm consist of several steps: *a*) estimation of network parameters; *b*) path selection; *c*) information evaluation and decision making; additionally to path parameters (metrics) also capabilities of a user device, video characteristics, feedback about previous transmissions, basic principles are taken into account; *d*) preparation of video streams (coding). Practical implementation of the algorithm requires cross layer information exchange and artificial intelligence for decision making. The algorithm considers several sources of information but particularly important are the network parameters which are used both by path selection and video coding. Problem of parameter estimation is addressed further in the chapter.

Video transmission over the networks is characterized by a set of parameters (metrics) describing network capability to ensure video transmission: bandwidth, packet-loss, delay and jitter. These metrics cannot be measured before a real traffic is transmitted but can be indirectly estimated with the help of other parameters. To find interconnections between parameters, the network behaviour during video transmission is analysed and the main influencing factors are identified: performance of the devices, protocols deployed (e.g. wireless standard, routing protocol, multiple-access technique), network topology (e.g. number of nodes, density), state of radio channel (e.g. fading, weather, mutually interfering devices), network dynamics (e.g. mobility of nodes) and network load created by other applications. The metrics are estimated in relation to the selected paths therefore the factors influence the network in combination with path selection algorithm. Path selection influences interference.

Since the paths are relatively close and antennas used in the devices have omni-directional radiation pattern the nodes of one path interfere with nodes in nearby paths (called inter-path interference). Impact of inter-path interference on aggregated path capacity has been investigated experimentally [16]. Similar research found is made with help of simulation only. For this purpose the author of the thesis has created ad-hoc network testbed with the following hardware and software solutions:

- 6 wireless routers *Cisco Linksys WRT160NL* supporting IEEE 802.11g/n standard;
- each router connected to *FSP Nano 360W* interruptible power supply;
- original firmware replaced by Linux distributive for embedded systems *OpenWRT* [17];
- ad-hoc network routing protocol OLSR [18];
- additionally installed *IPerf* network testing tool for data rate measurements [19].

Outdoor measurements were realised outside the city. Simple scenario was created by placing nodes in two paths m_1 and m_2 additionally connecting two portable computers to take measurements (illustrated in Figure 2.1). Typical transmission distance of standard wireless router is up to 100 meters. To perform experiment in a smaller area the transmission parameters were changed decreasing stable communication distance to ≈ 5 meters. *IPerf* tool was used to generate and send TCP traffic in both paths simultaneously and also take maximal data rate measurements. Data transmission in the first path was started later and ended earlier than in the second path, clearly showing interference period. The experiment was repeated with different distances between paths to gather data about several interference levels. Figure 2.2 presents the results.

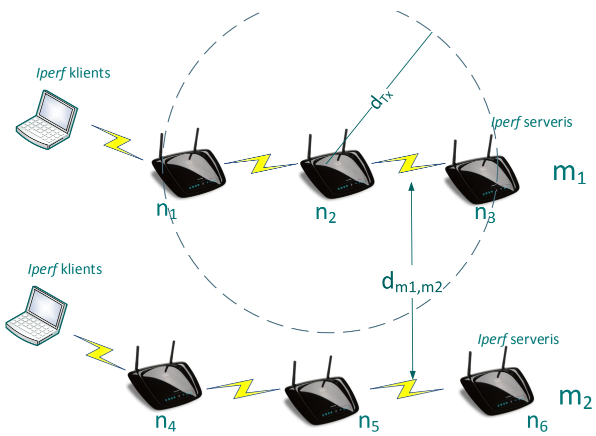
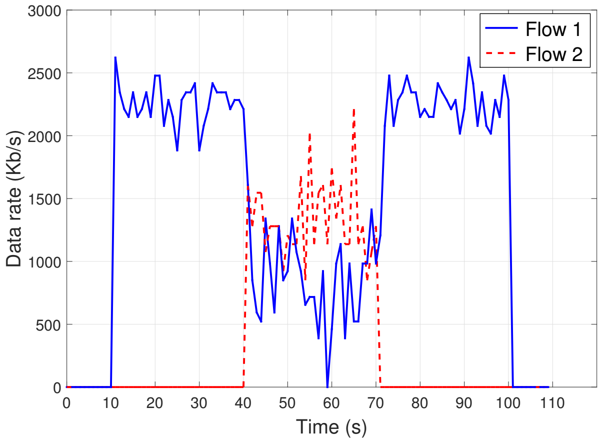


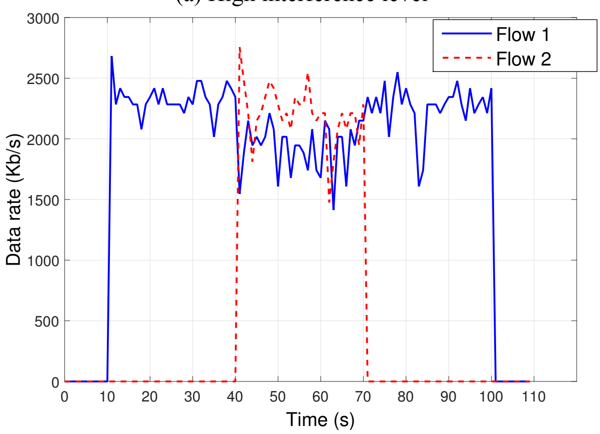
Figure 2.1: Experimental network topology with two paths

Figure 2.2a shows that when paths are close ($d_{m_1,m_2} = 7$ m) that is considered to be a high interference level multi-path transmission does not increase capacity. Aggregated data rate remains at the same level as for one path that is consistent with the previous research. Paths distance of 23 meters (considered as a low interference level) has almost no impact on data rate when transmission of the second stream is started (Figure 2.2b).

The main shortcoming of the testbed is a limited access for the equipment low level configuration that does not allow any modification of default Pysical Carrier Sense (PCS) threshold. For the investigation of PCS range influence on path capacity NS-2 network simulator is used. Multi-path scenarios with different inter-path distances and PCS thresholds have been simulated. Results show that each inter-path distance has its own optimal PCS threshold that means



(a) High interference level



(b) Low interference level

Figure 2.2: Data rate changes in each of the paths depending on inter-path interference intensity

that PCS tuning may help to decrease mutual impact of the paths.

Both studies demonstrate that inter-path interference is a key limiting factor for path capacity. Level of interference depends both on inter-path distance and PCS range.

As follows from analysis done in the chapter complex dependences exist among network parameters which are schematically summarized in ad-hoc network interrelationship model (Figure 2.3) [20]. The model visually links the factors that influence network with metrics important for video transmission. In such perspective and great variety of parameters a similar research cannot be found. On the basis of detailed analysis of interference two blocks are emphasized (radio interference and MAC contention) to show impact of these parameters on multi-path transmission efficiency. They affect all important metrics and are interlinked also to other parameters.

The model is useful for estimation of path metrics because it demonstrates logical steps to analyse network. Interconnection between parameters visually demonstrates which of the parameters must be taken into account to estimate metric. Possible measurements are also given for quantitative characteristic of the influence of one parameter on another. The model can help in the development of the program algorithms as it is shown in Chapter 4 where an elaboration network simulation tool has been described.

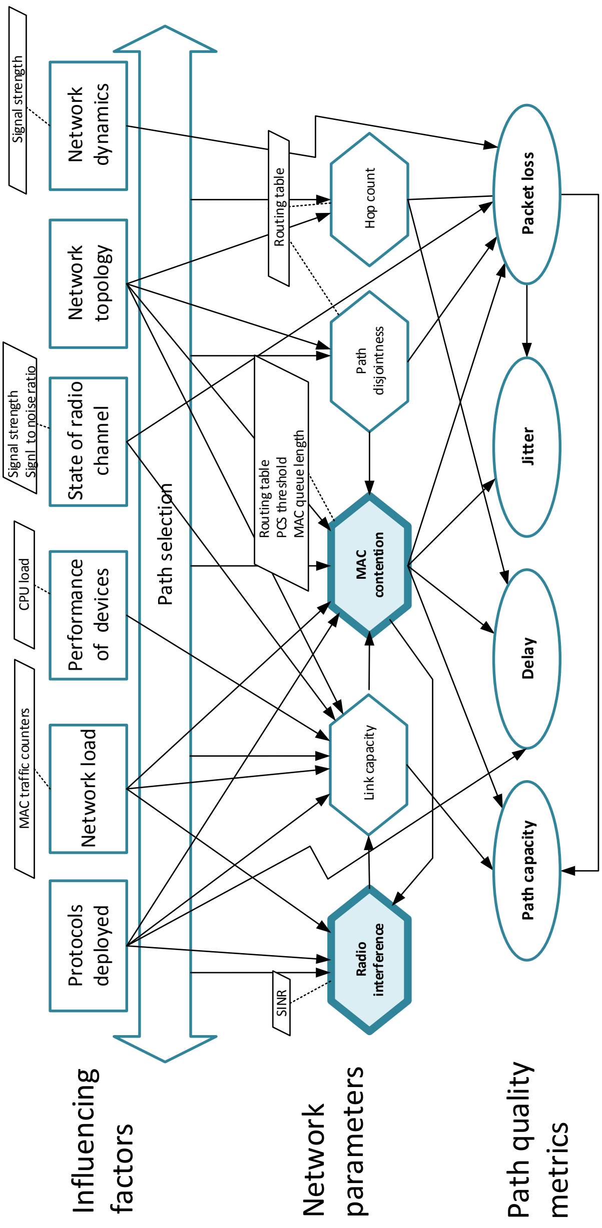


Figure 2.3: Network interrelationship model

3. Inter-path Interference Reduction

The analysis done in the previous chapter shows that if the data stream is split and transmitted over multiple paths the interference must be taken into account. Interference exists between nodes of the same path as well as between the nodes belonging to different paths which is called inter-path interference. It can decrease potential gain of multi-path transmission to zero. To decrease interference and improve multi-path transmission efficiency several approaches are proposed:

- selection of a suitable path set by taking into account interference (interference aware routing);
- application of smart antennas which decrease mutual interference and increase link date rate with the help of MIMO techniques;
- combination of both approaches to achieve synergistic effect: path selection is done by taking into account that smart antenna is used.

This chapter includes theoretical analysis to identify so far unresolved issues and clarify further tasks which are solved in Chapter 5 with computer simulation.

Selection of a suitable set of paths means to select a set with optimal number of paths and with less mutual impact. It is important to identify the factors influencing optimal number of paths. One of the objectives is to observe aggregated capacity dependence on the number of paths when interference exists.

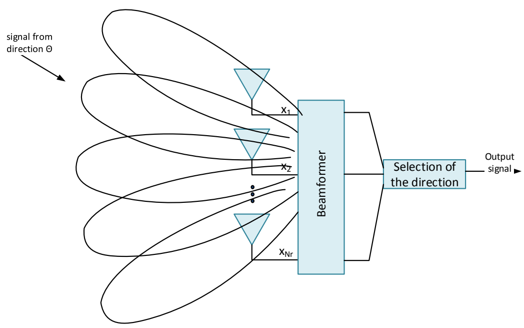
The majority multi-path protocols (e.g. SMR ,NDMR) uses a number of shared nodes as the main metric to characterize mutual impact of paths . It is a sufficient criteria to improve fault tolerance. But in its turn the increasing of load balancing or capacity aggregation gain require taking into account mutual impact because of internecine [21], [22]. It is proved experimentally in Chapter 2 (Figure 2.2). The best characteristic of mutual impact would be an achievable data rate of the paths however such metric is not beneficial from the practical point of view because high number of path combinations must be verified at path selection. In the thesis some path selection criteria based on easy detectable metrics but at the same time including interference have been sought. Mutual impact of the paths usually is characterised either with isolation at radio channel level [23], [24] (e.g. number of block nodes in nearby path) or spatial separation of paths [25], [22]. Spatial separation which is measured as inter-path distance has been studied in the thesis in detail. The paths with greater spatial separation are expected to result in a lower mutual interference but whether such paths provide higher aggregated capacity or not is not clear enough. The impact of inter-path distance on aggregated capacity is investigated and the conditions under which maximal distance is effective path selection criteria are analysed.

Smart antenna similar to multi-path transmission is intended to improve spatial reuse of radio channel. Smart antenna is antenna array which consists of several radiating elements. Digital Signal Processing (DSP) methods are used to process radio signal in each element to improve transmission efficiency. Smart antenna is a complex subject to be investigated therefore broader introduction to theoretical background and previous applications in ad-hoc networks are given in the chapter.

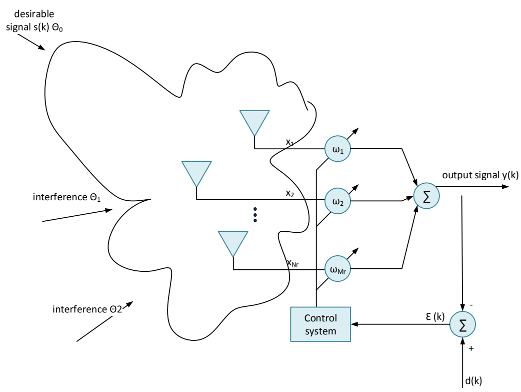
Several types of smart antennas are possible in ad-hoc networks which can be classified according to their application: directional or MIMO transmission. This research is based on two types of directional array antennas: beamsteered array and adaptive array. These allow changing far-field radiation pattern and provide directivity gain towards desired direction and attenuation in other directions (is is called beamforming). But the impact of array factor has been studied considering that array elements are isotropic radiators. The factor of linear antenna array is described with the model:

$$RF_{\theta} = \sum_{n=1}^{N} e^{\frac{-j\cdot(n-1)d\sin\theta}{c}} \tag{3.1}$$

where N – number of array elements;
θ – direction in azimuth plane;
d – distance between array elements;
c – speed of light.



(a) Beamsteered antenna array



(b) Adaptive antenna array

Figure 3.1: Types of directional antenna arrays used in the thesis

Adaptive antenna array is used also in MIMO transmission where signal multi-path propagation effects are exploited. By using antenna array both on transmitter and receiver side, signals from each array element of a transmitter arrive and are summed in each array element of a receiver. Mathematically such MIMO channel is described with the model (3.2).

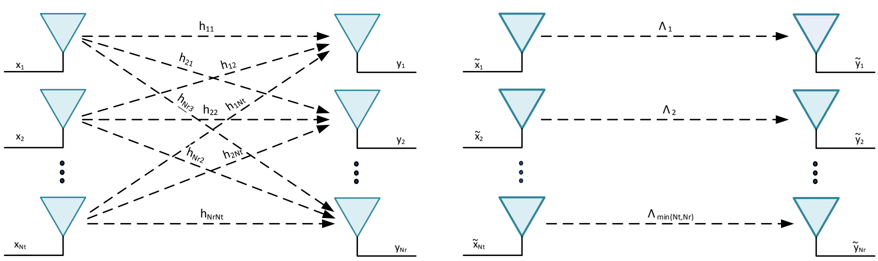
$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n} \tag{3.2}$$

where $\boldsymbol{H}$ – MIMO channel matrix $\begin{bmatrix} h_{11} & \cdots & h_{1N_t} \\ \vdots & \ddots & \vdots \\ h_{N_r1} & \cdots & h_{N_rN_t} \end{bmatrix}$;
$\boldsymbol{x}$ – signal vector in MIMO transmitter with length N_t;
$\boldsymbol{y}$ – signal vector MIMO receiver with length N_r;
$\boldsymbol{n}$ – noise in MIMO channel;

The DSP methods (e.g. singular value decomposition) makes possible to separate signals propagating over different paths if they are not correlated. Theoretically it enables up to $min(N_t, N_r)$ independent channels each with gain λ which are singular values of $\boldsymbol{H}$ (conceptual visualisation in Figure 3.2b). These channels are used to transmit parallel data streams and increase data rate which is called spatial multiplexing.

When MIMO is used in ad-hoc network, MIMO channel exists not only in each link but also between any two nodes belonging to paths creating in such way MIMO interference. A technique which combines MIMO spatial multiplexing with beamforming [26], [27] has been used in the thesis. In addition to data rate increase it provides also interference cancellation towards undesirable directions.

Analysis of existing solutions shows that application of smart antenna in ad-hoc network



(a) MIMO channel (b) Parallel MIMO sub-channels

Figure 3.2: MIMO system. N_t un N_r are number of elements in transmitter and receiver array

requires improvements in MAC and routing protocols. Directional transmission is not well supported from protocol side. MIMO implementation in IEEE 802.11n is effective for single hop transmission only [28] (traditional WLAN).

Potential gain of directional antennas has been extensively studied for single path transmission in ad-hoc network (e.g.[29], [14], [30]). Less work on multi-path and inter-path interference reduction can be found. For MIMO such studies cannot be found at all. To identify optimal conditions for application of directional antenna, additional studies with different main beam width (depending on N) and path set size should be performed. Increase of transmission distance due to power gain does not clearly improve capacity of ad-hoc network in general. It is useful to investigate the impact of directivity gain specifically on multi-path transmission.

Other important issue which is not researched in the case of multi-path transmission is a

Table 3.1

Comparison of antenna technologies for multi-path transmission

Multi-path characteristic	**Omni-directional**	**Directional**	**MIMO**
Several routes between single sender receiver pair	Complexity to find disjoint and non-interfering routes	Number of suitable path sets is increased. Route discovery and maintenance is complicated	Number of suitable path sets is increased if interference cancellation is considered
More nodes involved	Increased interference level. Higher total power consumption.	Physical interference is reduced. Number of nodes decreases if antenna gain is exploited	Link data rate is increased which in turn decreases MAC contention. Interference cancellation helps to avoid physical interference.
More hops per route because of interference necessity to separate them	Increased interference level. Higher delays and decreased reliability.	Routes are shorter if antenna gain is exploited. Main beam may interfere with the nodes in the same path.	
Paths are relatively close	Inter-path interference exist	If main beam is formed along the same path, inter-path interference decreases	
Endpoints operate in several spatially close directions	High interference level in the first and the last hop	If width of the main beam is sufficiently narrow interference decreases.	
Intensive data flow in paths	Increased MAC contention level because of high link utilization	MAC contention decreased because directivity improves spatial reuse.	

selection of suitable type of smart antenna. For general case this choice depends on environmental scattering of radio waves as well as topological and load parameters of the network. More effective are considered those antenna types which include adaptive beamforming techniques to cancel interference: these are adaptive directional antenna array and MIMO system with spatial multiplexing and beamforming. Based on the analysis carried out in the chapter as well as ad-hoc network interrelationship model, a comparison is made to highlight the benefits of smart antenna over omni-directional antennas particularly for multi-path transmission with intensive load (table 3.1) [31].

4. Elaboration of Method and Tools for Capacity Estimation

In the previous chapter several solutions to decrease interference have been proposed that have to be verified. Experimental evaluation requires great financial investments therefore computer simulation has been chosen. The evaluation must be independent on specific scenario and unpredictable parameters, e.g. topology and node placement. Still it has to reveal how much the parameters of interest like inter-path distance, number of array elements may influence aggregated path capacity. Such evaluation is possible by simulating a large number of random scenarios and estimating statistically average capacity as well as its variation trends as parameters change. It requires mathematical models which include interference cancellation and a method to estimate capacity in short time. Discrete event simulators as NS-2, OPNET which are widely used for elaboration and testing of protocols [11], [32] are not well suited for such task.

The applied hybrid method is based on maximal flow problem method known from graph theory and CSMA/CA simulation model which is elaborated in the thesis. Similar approach is used also in [5], [6], [33] but in the thesis the method has been improved with:

- additive interference which more precisely simulates CSMA/CA operation;
- additional constrains to estimate capacity of paths with shared nodes;
- models for directional and MIMO ad-hoc networks,

which is described in the author's publications [31], [34]. Numerical solution is sought for maximum flow problem because the method involves large number of variables that increases with the number of nodes. To solve it a linear optimisation is used with problem statement (4.5). Path capacity is estimated in several steps which are described independently further in the chapter:

1. according to the selected paths and interference model, sets of such links are sought that may operate simultaneously (further transmission schemes);
2. link data rate is calculated;
3. maximal flow rate in the paths is found.

1. Transmission scheme is a set of such links which can operate (transmit data) simultaneously. At one and the same time one scheme only is allowed to be active in the network. Transmission schemes are created according to constrains put by routing and interference model, additionally half-duplex constrain is taken into account. Example scenario with two paths is shown in Figure 4.1. Paths consist of six links forming set L:

$$\begin{Bmatrix} n_{11} \to n_2 \\ n_2 \to n_3 \\ n_3 \to n_6 \\ n_{11} \to n_9 \\ n_9 \to n_8 \\ n_8 \to n_6 \end{Bmatrix}$$

Transmission schemes are formed from the elements of set L. If interference is not taken into account, links can be grouped in the following schemes which is a complete variety (no other schemes are possible):

$$\begin{Bmatrix} n_2 \to n_3 \\ n_8 \to n_6 \\ n_{11} \to n_9 \end{Bmatrix} \quad \begin{Bmatrix} n_{11} \to n_2 \\ n_8 \to n_6 \end{Bmatrix} \quad \begin{Bmatrix} n_3 \to n_6 \\ n_9 \to n_8 \\ n_{11} \to n_2 \end{Bmatrix} \quad \begin{Bmatrix} n_3 \to n_6 \\ n_{11} \to n_9 \end{Bmatrix} \quad \begin{Bmatrix} n_2 \to n_3 \\ n_9 \to n_8 \end{Bmatrix}$$

The accordance of ad-hoc network model to real network conditions highly depends on interference model used. To simulate inter-path interference more precisely in contrast to similar research, an additive interference model is used. CSMA/CA protocol simulation model has been elaborated; it simulates PCS at a receiver by taking into account interference from all active links. Transmission schemes are formed in such way that interference level $P_{\sum I}$ which is sensed in any of transmitters belonging to the scheme when other links are active is less than

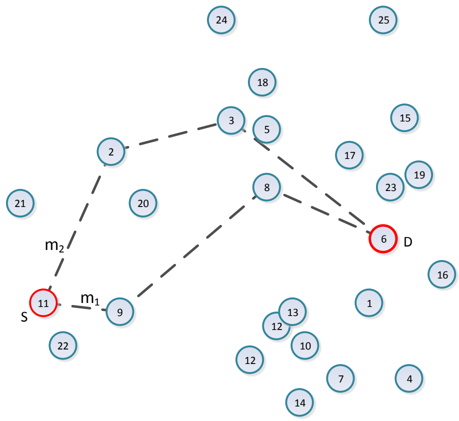


Figure 4.1: Example of scenario with two paths M_1 un M_2 between source n_{11} and destination n_6

PCS threshold P_{CST}. Also ambient noise P_N is considered. The condition is expressed as

$$P_{\sum I} + P_N < P_{CST} \tag{4.1}$$

$$P_{CST} > P_N \tag{4.2}$$

Applying the model to the scenario presented in Figure 4.1, the number of possible schemes will increase because some of the links are not allowed to be active at the same time.

It is a complex problem to find complete variety of transmissions schemes following condition (4.1) (e.g. for three path scenario when distance between source and destination is 11 hops, number of transmission schemes may reach 12000). For this task an effective simulation model has been created. It has been implemented as iterative process in which random link is taken from set L and put in the scheme; process is repeated until no link can be added to the scheme because of constrain (4.1). New schemes are formed until complete variety is found. There are several aspects that complicate the task:

- It is insufficient to verify whether a link which is selected for inclusion in a scheme does not interfere with any of already included links (conflict graph approach [5][33]). To implement additive model, before adding new link it must be verified how it influences cumulative interference $P_{\sum I}$ sensed at receivers belonging to the scheme so that in any combination it does not exceed P_{PCS} threshold.
- There is a necessity to verify whether newly formed transmission scheme is unique (it has not been created in previous attempts) which is computationally time-consuming task. To decrease verification time, the obtaining of identifier for each scheme (for example by adding up nodes indexes) and comparison at the identifier level are proposed.
- When set L includes a large number of links, finding complete variety of schemes is not beneficial. Empirical limit has been estimated when the algorithm should be stopped which is $25 \cdot num(L)$.

2. Calculation of data rate. Maximum data rate for each link in a transmission scheme is calculated taking into account interference from other links in the scheme. It is realised with the application of Signal to Interference plus Noise Ratio (SINR) model (4.3) which is the ratio between the received power of desired signal and the sum of powers of Gaussian (ambient) noise and interfering signals. Theoretical data rate limit between two nodes (link capacity) is determined with Shannon theorem (4.4).

$$\gamma = \frac{P_{Rx}}{P_N + P_{\sum I}} \tag{4.3}$$

$$C = B\, log_2(1+\gamma), \tag{4.4}$$

where P_{Rx} – power of received desired signal;
P_N – power of ambient noise;
$P_{\sum I}$ – power sum of interfering signals;
C – link capacity;
B – bandwidth of a channel.

Channel gain between nodes is calculated by means of combined path loss and shadowing radio wave propagation model [35].

Similar approach is used to calculate link capacity for transmissions with smart antennas but additionally an array factor must be taken into account. For directional transmission optimal antenna array weights are sought. For the analysis of MIMO in multi-hop network it is beneficial to abstract from physical processes and use degrees of freedom based models (e.g. [26], [27], [14]). In the best case when $\boldsymbol{H}$ is full rank an array with N elements provides N spatial degrees of freedom. Each node consumes one degree of freedom for each parallel data stream and one for interference cancellation towards other nodes. Interference cancellation is performed both on transmitter and receiver side.

3. Path capacity. The method considers that all transmissions (active links) operate in time slotted manner. Since all links share one radio channel, the channel time has to be divided between the links which are not allowed to operate simultaneously. It means to divide time between transmission schemes found in the first step. Weight p is used to characterise activity time of the scheme which has the following conditions: $0 \leq p_i \leq 1$ and $\sum_{i=1}^{k} p_i = 1$, where p_i is the weight (timeslot length) for transmission scheme with index i. The goal is to find such time schedule for full variety of schemes which provides maximal data flow rate between source and destination. Linear optimisation is used to solve maximum flow problem for ad-hoc network that is formulated in (4.5). It maximizes outgoing flows from source s taking into account constrains (4.6)-(4.9).

$$\max \sum_{l_{si} \in L} C_{si} \tag{4.5}$$

$$p_1 \boldsymbol{r}_1 + p_2 \boldsymbol{r}_2 + \cdots + p_k \boldsymbol{r}_k \leq \boldsymbol{c} \tag{4.6}$$

$$C_{ij} \geq 0 \qquad \forall l_{ij} \in L \tag{4.7}$$

$$C_{si} = C_{ij} \qquad \forall l_{ij} \in L \tag{4.8}$$

$$p_1 + p_2 + \cdots + p_k \leq 1 \tag{4.9}$$

where C_{si} – data flow rate from source s to neighbour i;
C_{ij} – capacity of a link belonging to set L;
k – number of transmission schemes;
$\boldsymbol{r}_k$ – vector of length L containing link capacities of scheme k, other elements are 0;
$\boldsymbol{c}$ – vector of length L containing weighted sum of capacity for each link.

For multi-path scenario the flow rate in the first hop of each path will be maximized. Since data rate within a path has to be uniform (constrain (4.8)) it automatically maximizes rate in all links belonging to the path.
Self evident is that the estimated capacity is theoretical and can be achieved with idealized MAC protocol but at the same time it shows potential of a path set. Such approach allows a mutual comparison of the path sets as well as evaluation of the effectiveness of techniques for interference decreasing. Better theoretical result indicates better results in the conditions closer to the real network. It is confirmed by comparing the results with NS-2 [4]. Strong correlation (≥ 0.5) has been observed for PCS range which is greater than double transmission distance. It results in the conclusion that the hybrid method can be effectively used to estimate capacity of multiple paths.

The method has been implemented practically as ad-hoc network simulation tool (Figure 4.2) which is programmed in Mathworks MATLAB environment (reflected in [34], [36]). Additional functions have been included for preparation of random scenarios, multi-path routing and smart antennas. Program code is available to the public in GitHub repository https://github.com/cikol/NetMat. Development of the modelling tool has followed the scheme of network interrelationship model (Figure 2.3). Several important factors and connections influencing capacity have been implemented: protocols deployed, state of radio channel, network topology, path selection, radio interference, MAC contention, link data rate, link disjointness, path capacity. This demonstrates the applicability of the interrelationship model.

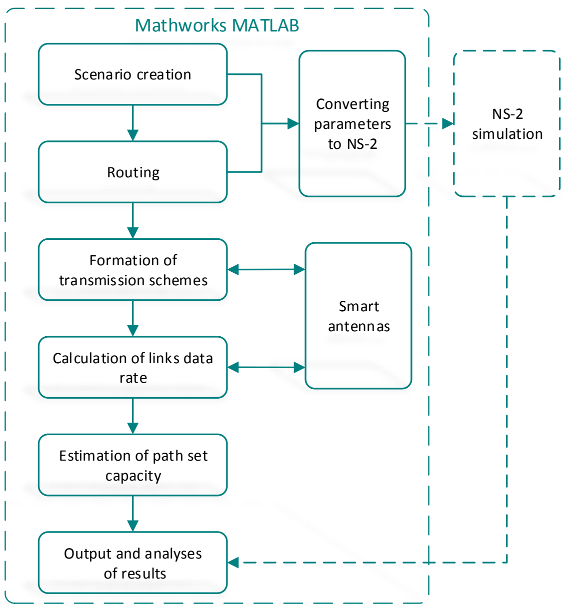
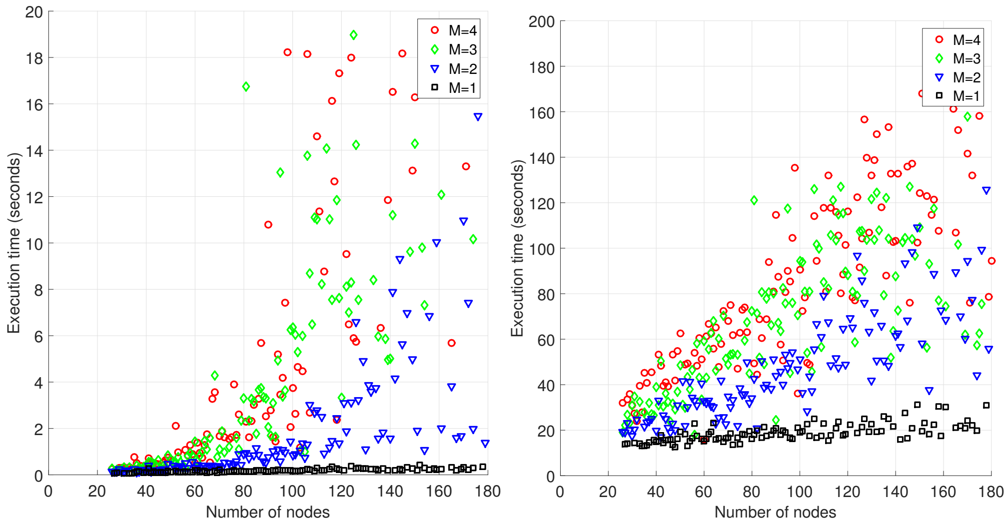


Figure 4.2: Block diagram of MATLAB tool

Simulation time of a scenario depends on the number of nodes, size of path set, number of antenna array elements and other parameters. The time also highly depends on PCS range as it influences a) the number of iterations to find complete variety of transmission schemes; b) number of variables in linear program (4.5). It has been estimated that the MATLAB simulation tool calculates capacity faster then NS-2 (in average 10 times), particularly when the number of nodes is high (Figure 4.3). One can observe that in both modelling environments time consumption increases also with the increasing of the number of paths. It must be taken into account that the time consumed by NS-2 depends on methodology of maximum rate recording. The results correspond to methodology used in the thesis but do not characterize NS-2 performance in general.



(a) Elaborated MATLAB tool

(b) NS-2

Figure 4.3: Time consumption for capacity estimation dependence on the number of nodes

The tool is intended to estimate the capacity for large number of random scenarios. Total time can be effectively decreased with parallel computing. The task involves a) Montecalro simulation and b) parameter sweep simulation with specific combinations of input parameters for each scenario. Distributed computing environment is well suited for such problems because it allows parallel processing of many independent tasks. For the research completed in Chapter 5 the HPC cluster of Riga Technical University is used with theoretical performance 20 TFlops. Within scope of the thesis the cluster has been prepared with MATLAB DCS module which was installed and tuned. Total time that would be needed on personal computer with performance equivalent to one Intel Xeon Central Procesor Unit (CPU) core to obtain results presented in Chapter 5 is about 37000 CPU hours or 1542 days.

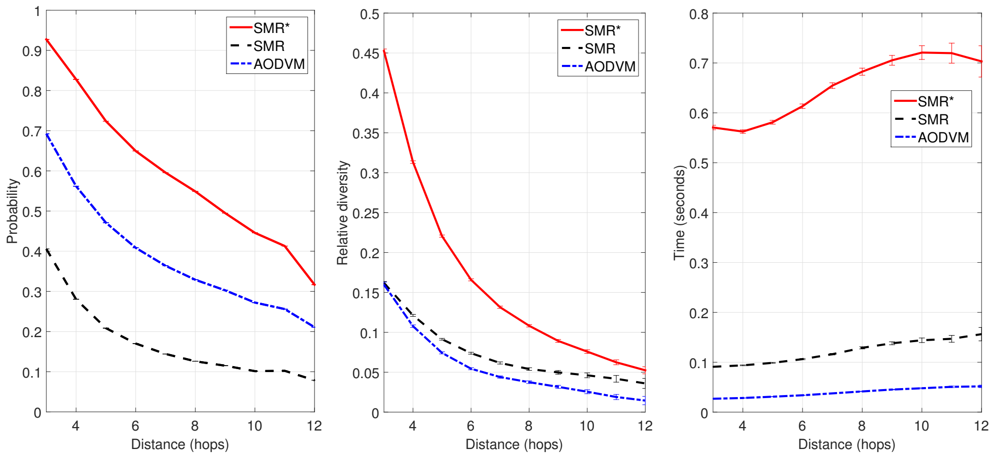
In the chapter SMR multi-path routing protocol has been improved and a simple MATLAB model has been elaborated for it (published in [36]). The protocol provides 2 – 3 times higher path set diversity between single source-destination pair in comparison to original SMR or AODVM protocol. In Figure 4.4 the efficiency of different path discovery algorithms is compared. The following performance metrics are used.

- Probability to find at least one path set in one route discovery attempt.
- Relative diversity found paths sets evaluated by Euclidean distance between the paths (estimation method is adapted from [22]). Relative diversity is calculated as d_{rel} =

$\frac{d_{max}-d_{min}}{d}$, where d_{max} is inter-path distance for the set which has the most spatially disjoint paths and d_{min} - less disjoint paths, d is direct distance between source and destination.

- Average time required to discover paths and create a path set.

Each performance metric is calculated as an average value of many results which are obtained by analysing total 240 random topologies in random size square field, for each topology 100 different source-destination pairs. As an argument on x axis hop count between source and destination is used. Hop count is determined by shortest path between source and destination. The results for two path scenarios only are shown. Figures 4.4a and 4.4b demonstrate that



(a) Probability find path set (b) Relative diversity of paths (c) Routing time

Figure 4.4: Performance of routing protocol

improved SMR (SMR*) finds path set with higher probability and path sets are more diverse if compared to SMR or AODV. Diversity is an essential factor for the research of path set selection criteria in Chapter 5. Higher protocol overhead is an adverse effect of diversity, which increases simulation time (Figure 4.4c). However, when protocol finds a path set with higher probability (as it is for SMR*) less routing attempts are needed. As a result average time to form a path set will be closer to other protocols.

5. Evaluation of Multi-path Transmission Efficiency

The main goal of the thesis is to improve data transmission efficiency in wireless ad-hoc network by using multi-path transmission and techniques to decrease interference. The previous chapters can be considered as a preparation for this: the situation has been analysed and network interrelationship model has been developed, solutions to decrease interference have been searched. At the end an analytical method which includes these solutions as well as MATLAB simulation tool has been elaborated.

This chapter considers the evaluation of the efficiency of multi-path transmission with the help of MATLAB tool. It is done by estimating statistically average path set capacity for large number of random scenarios. It involves random *a*) field size; *b*) node placement; *c*) source and destination selection; *d*) path set selection. Network parameters used in simulations are summarized in Table 5.1.

Table 5.1

Simulation parameters

General simulation parameters according to IEEE 802.11g/n standard	
Parameter	**Value**
Radio wave propagation model	Path loss with exponent $\alpha = 2$ or $\alpha = 4$
Transmission power P_{Tx}	0.1 W
Receiver sensitivity P_0	3.16e-11 W (75 dBm)
Maximal transmission distance d_{Tx} for diferrent path loss parameters	$\approx$ 547 meter for $\alpha = 2$ $\approx$ 23 meter for $\alpha = 4$
Edge size for scenario field	no $2 \cdot d_{Tx}$ līdz $8 \cdot d_{Tx}$
Noise	1.6e-13 W (-101 dBm)
Carrier frequency	2.45 GHz
Channel bandwidth	20 MHz
MAC	CSMA/CA with RTS/CTS off
PCS threshold (expressed as distance)	$2d_{Tx}$
Routing protocol	Improved SMR
Path set constrains	paths do not cross and are node disjoint

Parameters specific for smart antenna modelling	
Parameter	**Value**
Path loss parameter	$\alpha = 4$
Array element	Isotropic radiator
Number of array elements	similar for all nodes min. 2, max. 32
Distance between array elements	0.06 meters

Selection of suitable paths for multi-path transmission has been simulated involving optimal number of paths and selection criteria. Results (reflected in the author's publications [34][31][36]) confirm the findings of previous chapters about important factors influencing maximum data rate in ad-hoc network. Data rate mainly depends on the number of hops in a path between source and destination and mutual interference in data transmission process. In turn the number of hops depends on direct distance between source and destination and maximal transmission distance between the nodes and also path selection algorithm. Reduction of the number of hops is possible if directivity gain of smart antenna is used as it increases transmission distance between the nodes. Mutual interference depends on distance between paths, path loss parameter α in radio propagation model and smart antenna type.

If the distance between source and destination is small (2–4 hops), the highest data rate in ad-hoc network with omni-directional antenna can be achieved with one path (M=1). Multi-path transmission becomes more effective at greater distance (5 hops and more), however if path loss parameter is close to free space conditions $\alpha = 2$ benefit is negligible. At higher path loss $\alpha = 4$ the increasing number of paths from 1 to 3 gives maximum data rate increase up to 50%. The conclusion is that the most suitable conditions for multi-path transmission in ad-hoc network take place at higher path loss and distance between source and destination more than 4 hops.

At given simulation conditions 4–6 hops is a boundary at which the character of different factors influencing maximal data rate changes. It should be considered when one or other path selection criteria is applied. Three different criteria have been compared: set with the shortest node disjoint paths, set with maximal inter-path distance and random selection. For each scenario ($M = 2$ and $M = 3$) these criteria are applied to select possibly different path set between source and destination. The results show that for close distance (2–4 hops) between source and destination node-disjoint shortest path criteria provides 20% higher capacity. Maximal inter-path distance gives better result for 5–10 hops but the benefit is less (for $M = 3$ negligible). For a distance of 10 hops and more no difference statistically exists which of the criteria is to be used. Random selection does not provide better result in any case.

The research on omni-directional ad-hoc network is summarized in Figure 5.1. Aggregated capacity as a function of the number of hops is given for $M = 1$, $M = 2$ un $M = 3$ considering optimal path selection criteria described above. The figure clearly shows the critical boundary of distance between source and destination that must be exceeded to provide effective multi-path transmission. More detailed analysis has shown that the boundary is valid for different multi-path selection criteria.

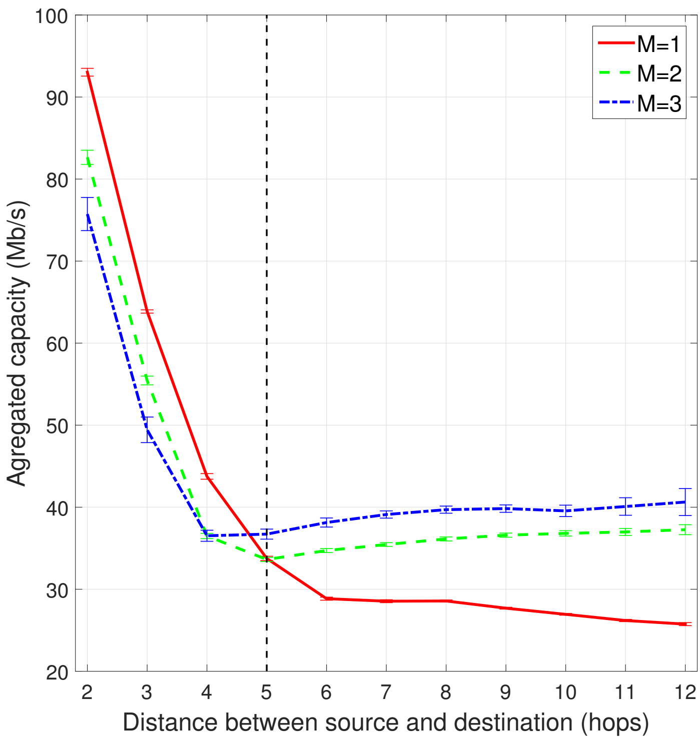


Figure 5.1: Multi-path transmission efficiency for omni-directional ad-hoc network

Maximum data rate can be increased when optimal path selection is combined with the application of smart antennas to decrease interference [31]. The following types of smart antennas have been compared:

1. beam-steered array without directivity gain (radiation pattern is normalized so that maximal transmission distance is equal to omni-directional transmission);
2. beam-steered array with directivity gain which increase channel gain between nodes N^2 times;

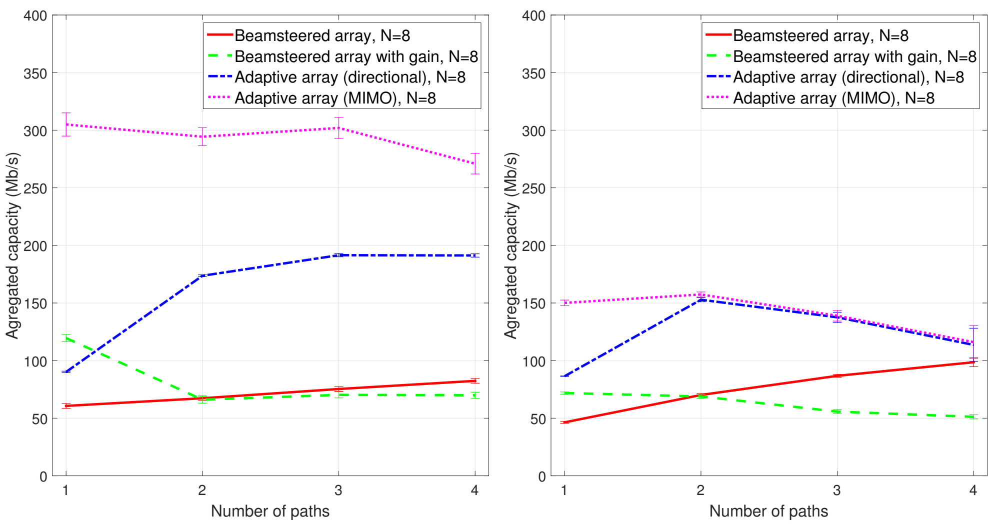
3. adaptive array for directional transmission without gain;
4. adaptive array providing MIMO Spatial Multiplexing (SM) with interference cancellation; total transmission power is uniformly distributed among sub-channels.

The network where all nodes use the same antenna parameters is considered.

Simulation results show:

- adaptive array in directional mode (one spatial data stream) provides maximum data rate increase when multiple paths are selected;
- MIMO mode provides overall highest data rate but it does not improve multi-path transmission efficiency;
- beam-steered array without directivity gain is more effective for multi-path transmission (decreases inter-path interference) if compared to beam-steered array exploiting gain which in turn performs better for transmission over single paths.

Smart antenna potential to decrease interference from other nodes mainly depends on the degrees of freedom determined by the number of array elements. If the number of interfering nodes increases that takes place when multiple paths are selected then the number of degrees of freedom also must be increased. For adaptive array at least 6 elements should be used. For multi-path transmission it is also more effective to consume degrees of freedom to decrease interference rather than to increase data rate with additional spatial streams. The results are summarized in Figure 5.2 where capacity as a function of the number of paths is given for different smart antenna types ($N = 8$). Two different ranges of distance between source and destination are given: 2–5 hops (Figure 5.2a) and 6 and more hops (Figure 5.2a).



(a) Distance is 2–5 hops

(b) Distance is 6+ hops

Figure 5.2: Aggregated capacity as a function of paths for different types of smart antenna

For smart antennas optimal path selection criteria depend on array type but has no dependence on the distance between source and destination. When beam-steered array is used, higher path capacity is provided by the set with maximal inter-path distance. For adaptive array when the degrees of freedom are sufficient to cancel interference all criteria provide similar result.

Research done in the chapter shows that optimal path selection improves data transmission efficiency and it is important also when smart antennas are used. Selection is done by taking into account the parameters which characterize the network. To summarize results the guidelines have been elaborated that help to select optimal paths considering antenna type (omni-directional or smart) and network parameters (path loss parameter α, distance between source and destination, number of array elements N). Guidelines can be used in interference-aware routing protocols for decision making algorithms.
For omni-directional antenna the following guidelines should be followed.

- In environment which has free space radio wave propagation characteristics a single shortest path is selected.
- When propagation loss is higher $\alpha = 4$, the distance between source and destination is taken into account. If distance is 2–4 hops, a single shortest paths is selected but if 5 hops and more then 2–3 paths with greater spatial separation (maximal distance criteria).

For smart antenna the following guidelines should be followed.

- For beamsteered array without directivity gain the distance between source and destination is taken into account. For close distance (2–4 hops) and if $N \leq 6$, a single shortest path is selected, if $N \geq 8$ up to 4 maximally disjoint paths are selected. For greater distance the optimal number of paths is up to 3 with maximal inter-path distance irrespective of N.
- For beamsteered array with directivity gain single shortest path is selected irrespective of N.
- For adaptive array in directional mode if $N \leq 4$ single shortest path is selected, if N is greater up to 2 paths is selected. In both cases the shortest path is an appropriate selection criteria.
- When adaptive array in MIMO mode is used, the most effective data transmission is over single path irrespective of N.

Research made in the chapter focuses mainly on interference effects therefore static network topologies have been considered. However, the guidelines can be applied also to mobile scenarios if metrics characterizing interference are combined with metrics characterizing mobility.

The Main Results and Conclusion

The research has been done on improving data transmission efficiency in IEEE 802.11g/n standard based wireless ad-hoc network by using multi-path transmission and techniques to decrease interference. Data transmission efficiency is improved that is presented further in the summary of the main results and conclusion.

Video transmission is one the services which is the most difficult to be ensured because of strict requirements for a network. At the same time its topicality keeps increasing therefore video transmission is used as a pilot application for the research of the thesis. One of the factors limiting video transmission in ad-hoc network is mutual interference of nodes that decreases data rate. As a solution multi-path transmission has been chosen as it has a potential to increase data rate and requires less changes to IEEE 802.11 standard itself.

Existing video coding and routing techniques for video transmission over multiple paths have been analysed and conceptual algorithm ensuring optimal transmission has been developed. Implementation of the algorithm requires OSI cross-layer approaches, particularly information from lower layers about important path metrics (capacity, delay, jitter, packet loss). The factors influencing the network that should be taken into account to estimate metrics before real video transmission: performance of the devices, protocols deployed, network topology, state of radio channel, network dynamics, load created by other applications as well as path selection. **The analysis has been schematically summarized in network parameter interrelationship model.** The model visually links the factors influencing the network with metrics important for video transmission and shows logical scheme to analyse the network.

Experiment made in IEEE 802.11g/n ad-hoc network testbed and simulation in NS-2 shows interference as one of the main factors limiting capacity when data is transmitted over multiple paths. If the nodes of two paths mutually interfere then multi-path transmission does not increase the aggregated capacity. Intensity of inter-path interference depends on spatial disjointness of the paths and physical carrier sense operation distance.

To improve multi-path transmission efficiency, the techniques for decreasing of interference must be used. In the thesis interference aware path selection and application of smart antennas have been studied. Effectiveness of the techniques has been evaluated by means of computer simulation estimating the influence on statistically average capacity of a path set.

Capacity of multiple paths can be effectively estimated with a method which combines maximum flow method and simulation model elaborated in the thesis which include additive interference. The model simulates operation CSMA/CA at transmitter side. The results show strong correlation (≥ 05) with the "Network Simulator 2" output.

The method has been implemented in MATLAB environment as an ad-hoc network simulation tool. The tool includes additional modules for preparation of random network scenarios, multi-path routing and smart antennas.

- Improved path discovery algorithm for SMR multi-path routing protocol, for which MATLAB model has been elaborated, provides paths sets with 2–3 times higher diversity if compared to original SMR or AODV protocol.
- It is beneficial to use the degrees of freedom based models for smart antenna analysis which simplifies capacity calculation in multi-hop conditions.
- The simulation tool provides the results in average 10 times faster if to compare to NS-2 that makes it convenient for analysis of many scenarios. Total time has been effectively decreased by parallel calculation in HPC cluster.

Interference is decreased if suitable path set is selected with an optimal number of paths and according to optimal criteria. Both selection parameters depend on a distance between source and destination. **Multi-path transmission is effective when the distance between source and destination is greater than specific boundary (in the thesis 5 hops) and the boundary is valid also for different multi-path selection criteria.** When optimal criteria are taken into account, 3 paths provide capacity increase up to 50% if compared to single path. For shorter distances (2–4 hops) the highest data rate is achieved with a single path.

Data rate is effectively increased when optimal path selection is combined with an application of smart antennas. Comparing the potential of several smart antenna types to decrease inter-path interference the directional antenna arrays are determined as more effective than

MIMO as the capacity is increased with the use of multiple paths. **Adaptive antenna array with single spatial stream provides maximal data rate improvement** – aggregated path set capacity is doubled when a sufficient number of degrees of freedom ($N \geq 8$) is ensured. Directivity gain for beamsteered array increases data rate because shorter path can be established but its usage is beneficial only for single path transmission.

The results are summarised in guidelines which help to select optimal paths considering antenna type and network parameters. The guidelines can be used in interference-aware routing protocols for decision making algorithms.

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