# Design and Scheduling in 5G Stationary and Mobile Communication Systems Based on Wireless Millimeter-Wave Mesh Networks

Vladimir Vishnevsky, Andrey Larionov(✉), and Sergey Frolov

V.A. Trapeznikov Institute of Control Sciences of Russian Academy of Sciences,
65 Profsoyuznaya Street, Moscow 117997, Russia
vishn@inbox.ru, larioandr@gmail.com, sergey@frolov.ru
http://www.ipu.ru/en

**Abstract.** The paper presents the concept of local and metropolitan wireless mesh networks operating in millimeter-wave band. These self-organizing networks may be used as the high-throughput backbones for emerging 5G communication systems, as well as standalone networks providing extensive QoS, mobility, reliability and ultra-high throughputs for the connected users. The paper observes the current state and the prospects of the development of the millimeter-wave mesh networks. The paper outlines the network logical structure including MAC level design, routing and resource allocation. The problem of delay-optimal scheduling within Spatial TDMA is formulated, and a simple fast algorithm for scheduling is proposed. The experimental results provided prove the algorithm allows to utilize the network resources at very high rates while building scheduling sufficient for delay-critical applications.

**Keywords:** Wireless mesh networks · STDMA · Millimeter-wave networks · Optimal scheduling · 5G networks

## 1 Introduction

Centimeter wave broadband wireless networks are currently one of the main trends in the telecommunication industry. Wireless networks including UMTS, cdma-200, WiFi (IEEE 802.11), WiMax (IEEE 802.16) are widely spread, have many advantages including rapid installation, mobility, price, often becoming the only cost-efficient solution.

However the high occupation of the centimeter band imposes strict restrictions on the allowed bandwidths and, consequently, limits the information transfere rate. In particular, WiFi network equipment that operates in the centimetric band 2.4–6.4 GHz, provides a nominal speed of 54 Mbit/s with a broadband of 20 MHz and 108 Mbit/s turbo at 40 MHz. The equipment that implements a new standard IEEE 802.11-2012 [2] and using MIMO technology provides the maximum data transfer speeds up to 600 Mbit/s. However, even these rates implemented on the basis of traditional technologies are not sufficient to satisfy the

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quickly and continuously growing volume of multimedia information. To this end, lots of research centers all over the world are working hard to dramaticaly increase the performance in the wireless networks.

One of the main trends in the development of the ultra-high capacity (over 1 Gbps) wireless networks is the transition from the traditional centimeter-wave band to the millimeter-wave band (60–100 GHz). This transition is characterized as a new wave of innovation in the area of wireless communications, comparable to the advent of the cellular standards and the invention of WiFi [4–6].

Although the millimeter-wave has been attracting the attention of the networks developers for a long time, but its practical usage in the telecommunication systems was limited by the 40 GHz until recently. Following the adoption of licensing regulations in 2005 by the Federal Communications Commission, a number of the first millimeter wave radio equipment appeared. In 2006, the European Institute of Telecommunications Standards (ETSI) has published technical rules on equipment operating in the E -band frequencies (71–76 and 81–86 GHz). These regulations conform to EU requirements and allow commercial use of the wireless E-band equipment in Europe. By today, many countries are adopting the E-band for wireless point-to-point communication systems, working in the short-wave part of the millimeter range.

The mm-wave electronic components with acceptable characteristics and price appearance, the increased centimeter-wave band occupancy and the novel multimedia applications development lead to the practical development of the E-band communication systems.

The low millimeter-wave band occupancy, the wide bandwidth allocation possibility (up to 5 GHz), the simplified spectrum regulations make the mm-wave band a unique choice for the implementation of personal, local, regional or metropolitan area networks, as well as for the point-to-point communication systems. Other advantages of the mm-wave band include but not limited to:

- ultra-high data transfere rate up to 10 Gbps;
- the possibility of creating miniature phased array antenna systems. It is even possible to create chipset-integrated antenna systems, as achieving a narrow radioation pattern for greater antenna gain require smaller antenna size;
- the heavy signal attenuation in the mm-wave band is an advantage as it limits the signal propagation distance and simplifies the frequency planning task;
- it is possible to implement different scrambling schemes, error-correction coding, utilize simple modulation schemes and multiple access methods;
- the narrow-band communications secrecy and integrity, i.e. the resistance to interference and attempts for unauthorized connections.

The nowadays existing mm-wave band telecommunication solutions may be broadly divided into two parts: point-to-point communication systems and personal area networks (PAN). The point-to-point communication systems are used rather often by LTE or WiMax networks operators to interconnect the base stations, or to build a wireless connection between buildings. These systems provide very fast connections with up to 10 Gbps speed, but are very expensive, require manual configuration and normally can not be used to build a cost-efficient network, covering a relatively large area, or to build a local network comprising many nodes with the up to 100 m distances. The PAN standard IEEE 802.15.3 amendement IEEE 802.15.3c "Millemeter-Wave-based Alternative Physical Layer Extension" was published in 2009, October. In November, 2009 the European standard ECMA-387 "High Rate 60 GHz PHY, MAC and HDMI PAL" was published [3]. These two standards cover the personal area networks operating in 60 GHz. One of the main applications of these technologies is to provide multimedia system components with wireless connections, replacing HDMI cables with wireless links. One should also mention the Wireless Gigabit Alliance (WiGig), found on May, 2009 by a number of industry leaders including Atheros, Broadcom, Dell, Intel, LG Electronics, Marvell, Microsoft, NEC, Nokia, Panasonic, Samsung Electronics and others. NXP, Realtek, STMicroelectronics, Tensorcom, Cisco, Texas Instruments and many other companies also entered the alliance later. By now, the specification produced under the WiGig alliance is included in the amendment IEEE 802.11ad, which final version was recently published. The standard enables to use 60 GHz spectrum in line-of-sight communications, at rather close distances to significantly boost the communications speed. Nevertheless, there are no existing solutions for building local, regional or metropolitan area networks with mm-wave equipment.

The outlined advantages of the mm-wave band for communications systems development coupled with the weaknesses of the existing centimeter-wave solutions, the increased throughput requirements introduced by the modern applications and the lack of scalable cost-effective mm-wave wireless solutions for implementing LANs and MANs, raise the actuality of the mm-wave multihop wireless mesh networks design and development.

The mm-wave mesh network will be overviewed in the next station. Afterwards, the base station protocol stack design will be presented. Finally, the paper will focus on time resources scheduling, which is one of the most significant part of the TDMA-based channel access method used in the network.

## 2 Millimeter-Wave Mesh Network Design

The self-organizing wireless millimeter-wave mesh network is formed by a number of base stations. The base stations functions include networks and neighborhood discovery, associations establishment, links management, user traffic transmission and bridging with existing wired and wireless networks like Ethernet, WiFi, WiMax, LTE and others. Each base station includes a frequency-duplexing transceiver, allowing to send and receive data simultaneously using two separate frequencies, which significantly increases the base station throughput. Figure 1 gives an example of a small mesh network.

The protocols forming the base station stack were designed with scalability in mind so the network is able to provide sufficient delays and throughputs characteristics when consisting of more then 100 base stations. Taking into account a typical distance of 500 m between neighbour stations the network may cover an area of $5 \times 5$ kilometers or even more.

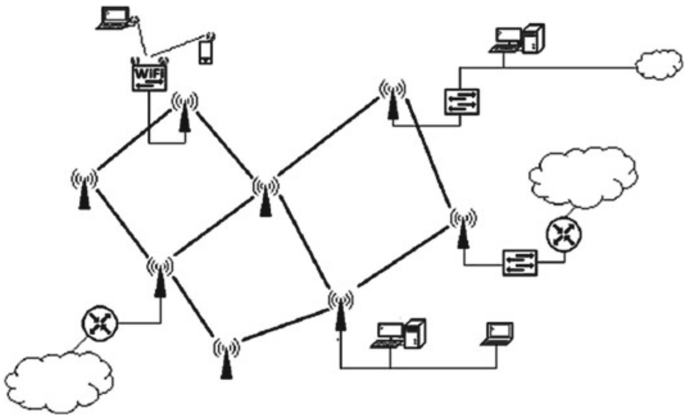


**Fig. 1.** Wireless mm-wave backbone mesh network example.

Each base station automatically selects the frequency pair when joining the network. The frequency pair choice made by the base station determine its possible connections. Say, if station $A$ choosed frequency $F_1$ for transmitting and $F_2$ for receiving then it will be able to establish the connections with the stations using $F_2$ for transmitting and $F_1$ for receiving. The frequency assignment may be changed afterwards as a result of topology change, station movement or any other reason.

The network throughput is further increased due to the very low interference. To achieve high antenna gain the base stations transceivers use antenna arrays forming narrow beams which also allows avoiding collisions between densely spaced transmissions. The mm-wave signal heavy attenuation further reduces the collisions probability. These factors make it possible to ignore the interference in most cases however one must pay the attention to the transmissions coordination and synchronization both over the time and over the space.

Each base station comprises the only transceiver. Consequently, the base station is able to perform a single upload and a single download simultaneously. Because of this the maximum number of neighbours limit was forced (four stations, by default) as otherwise in some scenarios the link throughput may become arbitrary small.

The channel access method used in the network is Spatial TDMA [7]. Time scheduling is performed both localy by the stations, and centraly by the *root station*. For instance, the neighbour stations may decide to temporary boost their connection by allocating an additional time interval for it while the root station is in charge of more complicated scheduling functions, including time intervals allocation for multihop transmissions and spanning trees. The multihop transmission that was scheduled by the root station is called a *virtual channel*. The root allocates the same time value for all links transmitting a given virtual channel, so neither channel may have a bottleneck. Virtual channels and spanning trees are being used for extensive QoS support to allow transmitting the most critical or preprovisioned user data being sent with minimal delay and maximal priority. The STDMA implementation and scheduling will be discovered in more details in further sections. Time synchronization which is critical for any TDMA-based access is achieved using GPS/GLONASS adapters.

To bridge with miscellaneous local networks base stations implement IEEE 802.1D [14] bridge standard. This allows connecting the mesh network with existing networks including Ethernet, WiFi, WiMax and others.

## 3 MAC Layer Architecture

The base station MAC layer is in charge of links management, channel access and STDMA scheduling, network discovery, association and disassociation, mobility managment, frames routing, external networks discovery, root station election, and other essential functions. The layer structure is presented in the Fig. 2.

The primary MAC layer services include the following:

- *Traffic classification* and *queueing management* services for QoS management.
- A proactive routing protocol *Mesh Link State Routing (MLSR)* which is used as a default routing facility. The protocol is based on OSPF [15] and OLSR being adjusted for the mm-wave mesh network characteristics.
- Network discovery, association and disassociation, links management, local scheduling and other essential management functions are implemented in *Mesh Management (MMAN)* service.
- *Mesh Resource Allocation Protocol (MRAP)* is in charge of transmitting virtual channels creation, modification or deletion requests and schedules propagation.

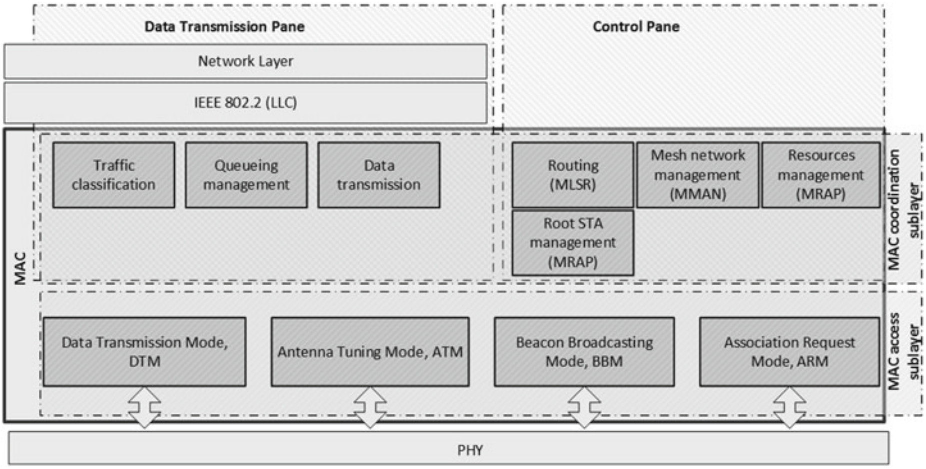


**Fig. 2.** MAC layer design.

– The root base station election, backup root stations selection, configuration and synchronization along with other root-related management functions are provided by the *Mesh Root Management Protocol*.

The base station uses several PHY-layer access modes:

– *Data transmission mode (DTM)* is used to transmit user, control and management frames through the link.
– Neighbour stations may adjust their antennas configurations to decrease the error rate using *Antenna Tuning Mode (ATM)*.
– Each associated base station periodically transmit a special Beacon-frame simulating broadcast in *Beacon Broadcasting Mode (BBM)*.
– *Association Request Mode (ARM)* is being used by the station that would like to associate with the network or to create a link with a new neighbour.

## 4 Scheduling in Spatial TDMA

The efficiency of any Spatial TDMA implementation depends heavily on the time scheduling algorithms. The quality of schedules being built affects the end-to-end delays for multi-hop transmissions, the stations and network throughputs and even the load balancing. These characteristics depend on the scheduling algorithm type, the criteria that was utilized and, of course, on the algorithm design and implementation. Many of the scheduling problems are NP-complete, so usually there is no straight way to achieve the optimal characteristics.

There are several ways to implement scheduling within Spatial TDMA, and some of them are used in the mm-wave mesh network MAC layer. These methods are observed briefly below, then a detailed review of the Spatial TDMA implementation is presented and finally we give the heuristic algorithm along with its simulation results.

First of all, the stations or links may be granted the equal time intervals to communicate with the neighbours, i.e. each station periodically has a time interval when it can send its data to the neighbours or receive data from them. These intervals can be selected when the station enters the network, so neither coordinator nor any complex network knowledge is required. If the station needs to discover a remote station that is not in its strict neighbourhood, the standard protocols like AODV [17], OLSR [16] or HWMP [2] may be used. To implement this type of scheduling one needs to synchronize the stations and find a way to allocate the slots for the new stations entering the network or to schedule the new links when the network topology changes. Despite of the fact that the slots allocation for each link may be reduced to the edge-coloring problem, in many instances this approach may be implemented relatively simply and it doesn't require lots of computational resources but lacks the ability to support multihop transmissions at the stage of time-resources allocation.

Another local scheduling approach is based on the idea that some stations act as access points to the others. These access points may broadcast beacons to indicate the superframe start, send out timing and resource allocations parameters, and perform the scheduling [1]. Whenever a station A that is connected to the access point B needs a time slot to transmit its data, it sends a request to the access point. The access point schedules the requested transmission and informs the client about the slot starting time and its duration. This approach is widely used in many wireless networks including IEEE 802.11, IEEE 802.16 and IEEE 802.15.4.

On the other hand, the schedule may be built for a large group of stations. For example, some dedicated server station may accumulate all bandwidth requests from all stations, build the schedule for the whole network at once and propagate the schedule over the network. The slots in the schedule may be allocated to provide the optimal access for separate stations depending on their current load, as well as to provide the time resources for multihop transmissions based on the information of the running applications QoS requirements, including bandwidth and timing limitations. The latter approach allows uniform scheduling the multihop transmissions over all their paths at once thus avoiding the bottlenecks: if the station A sends some data to the remote station D through their common neighbour C, the schedule will contain the equal number of slots for both A-C and C-D transmissions. The same task may be solved faster and in more reliable way by some distributed resource allocation protocol without the dedicated central station, though using the server can lead to better schedules. The server-based approach for multihop transmissions scheduling is discussed below more detailing as it is used in the mm-wave mesh network base station MAC level.

Prior to build the scheduling algorithm one needs to determine the criterias to be optimized in the produced schedules. Lots of prior work, see [8–13], was focused on building the minimal-length schedules, as well as on maximizing the absolute and relative throughputs or minimizing the schedules delay. The widely used approach for building the algorithms maximizing the throughputs or minimizing the multihop transmissions delays is to decompose the problem into two parts: routing and time slots allocation. This decomposition allows simplifying the original task: the first part may be solved by the well-studied methods including Dijkstra, Bellman-Ford or Floyd-Warshall algorithms [18]. Unfortunately, the optimal time slots allocation problems for minimizing delay or maximizing the throughput are NP-complete.

## 4.1 Spatial TDMA Implementation

According to Spatial TDMA scheme the links should be granted time intervals. Considering the wireless networks, TDMA-based channel access methods usually have to account interference. To avoid the collisions while transmitting over interfering links these links must be scheduled in different time intervals. However, since the heavy attenuation in the mm-wave band and the narrow beams used by the base stations, the interference in the mm-wave mesh network may be neglected. This allows assuming just two possible types of conflicts to be different transmissions simultaneous receptions by the same station and the simultaneous transmissions by the same station to different neighbours.

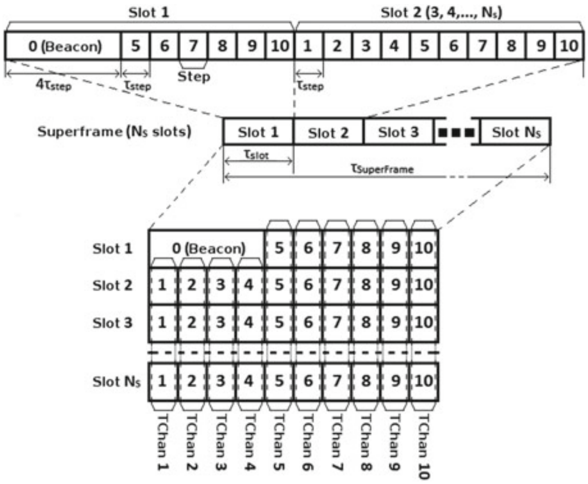


**Fig. 3.** STDMA time intervals and superframe structure.

The drawback of the narrow beams is that any time the station may send its data to only one neighbour, so it is impossible to use the broadcast nature of the wireless transmission.

MAC layer uses the three-layered time gradation, see Fig. 3. Time is divided into **steps**. The step is the shortest time interval that can be granted to any link. The step acts like a slot in the described above scheduling methods. A typical step duration is 100 us. Each ten consequent steps form a **slot**, which is 1 ms by default. The slot is a periodic structure used in the basic access: every link has one associated step to transmit in both directions during each slot. The step is assigned when the connection is established but can be changed afterwards. By default, first four steps in each slot are used for such assignment. Consequently, each station can have four connections at most by default. Other steps (six by default) are scheduled dynamically either by the negotiation between the neighbours, or by the root station. Several consequent slots forms a **superframe**. Superframes are being used by the root station for scheduling spanning trees and multihop transmissions. The superframe duration may vary depending on actual network size and load. A typical superframe duration for the network consisting of 100 stations operating under the heavy load is 50 ms. It should not be too large as this will increase the overall delay in the network while too small superframe duration values may decrease the quality of multihop transmissions serving.

The mm-wave mesh network implements several scheduling methods utilizing different scheduling approaches. The basic access method states that each station is being granted one step in each slot for each neighbour it has. Because of the full-duplex nature of the base stations, the network topology may be represented with a bipartite graph. The task of assigning each link to one step in each slot may be reduced to the edge coloring problem which is easily solved for bipartite graphs: the number of colors is always equal to the maximal node degree. Since the maximum number of neighbours is limited by four by default, the number of different steps needed to schedule all the links in the network is also four (if there exists a station with four neighbours).

The steps not distributed uniformly according to the first approach may be used in three different ways. First of all, these steps can be temporary captured by the neighbours to boost their connection in the case of increased traffic load. The neighbours may negotiate a step that is available for both stations and use it in the same slot to temporary increase their connection capacity.

Secondly, the root station provides the network with a schedule for transmitting data over the spanning tree. The trees transmitting schedule comprises two parts: data aggregation and data propagation. The data aggregation part is used to forward data from all stations to the root while the data propagation part following the aggregation is being used to propagate the data from the root to all other stations in the network. The whole tree schedule fits into the superframe, so any data fitting into the steps allocated for the tree will be delivered to the destination during the time interval, limited by the superframe length.

Finally, the central station builds the schedule minimizing the multihop transmissions delay and balancing the network load. If station A needs to create a virtual channel to station B with specific capacity and delay requirements, it sends the request to the root. The root collects the virtual channels creation, modification and deletion requests, rebuilds the schedule for all collected requests and propagates this schedule over the network. Each virtual channel may consist of several different paths, the only requirement is that each link that belongs to the path obtains the same number of steps in the schedule. The station that originated the virtual channel creation request is obliged to primarily use the created channel for the traffic it requested the channel for.

The root station builds spanning tree and multihop transmissions schedules for the duration of the superframe. For example, if the superframe consists of 50 consequent slots, and each slot uses its first 4 steps for the basic access (uniform distribution of the steps between the links), then the schedule will occupy 300 steps. Unless the schedule being updated by the root, all the stations use the same schedule. This means that if station $A$ was scheduled to transmit data of the virtual channel $h$ to station $B$ during the step $s$ then station $A$ will transmit another portion of channel $h$ in the same step $s$ of the current superframe, the next superframe and so on. Because the first steps used in the basic access method are never utilized by the schedules, they will be further ignored to simplify the algorithms and computations. For the example given above, it is supposed that the superframe consists of the 300 sequential steps.

To figure out the nature of the delay in the multihop path, consider the schedule for path $A \rightarrow B \rightarrow C$. Let $s_{AB}$ be the step number assigned to the link $A \rightarrow B$, and $s_{BC}$ be the step number assigned to the link $B \rightarrow C$. If $s_{AB} < s_{BC}$, the link $A \rightarrow B$ is scheduled prior to the link $B \rightarrow C$ and the delay is $s_{BC} - s_{AB}$. Since all the steps are scheduled within a single superframe, the path delay will be limited by the superframe length $d$. But if the link $B \rightarrow C$ is scheduled prior to the link $A \to B$ then the single message can not be transmitted during one superframe: at the time a message arrives at station $B$, the station $B$ order to transmit to station $C$ had passed and station $B$ has to wait for the next superframe to send the message over the link $B \to C$. This means that in case when $s_{AB} \geq s_{BC}$ the path delay will be calculated as $s_{BC} + d - s_{AB}$ where $d$ is the superframe length. The occasion when some link is scheduled prior to the previous link will be called **inversion**. If path $\pi$ has $n$ inversions its delay $\delta \in [nd, (n+1)d]$.

Let the bipartide digraph $G =< V, E >$ where $|V| = N, |E| = M$ and $e_1 = (v, u) \in E \Leftrightarrow\ e_2 = (u, v) \in E \Leftrightarrow$ [stations $v, u$ are connected] represent the network. Let $C = \{c_{ij}\} \in \{0, 1\}^{N \times N}$ be the vertex incidence matrix.

The superframe consists of $T$ steps, $E$ is the step duration and $B$ is the link capacity. Each step can transmit $E \times B$ at most. The virtual channel request is divided into $k = \lceil r/(E \times B) \rceil$ subrequests. If the virtual channel requested capacity $r > E \times B$ it compirses more then one subrequest. Each subrequest capacity is assumed to be equal to $B$ so there is no need to hold the capacity in the subrequest description. The subrequest can be represented with a couple $< u, v >$ where $u \in V$ is the channel source and $v \in V$ is the channel sink. Let $S = \{< u_1, v_1 >, < u_2, v_2 > \ldots, < u_R, v_R >\}$ be the set of all subrequests and $|S| = R$. In the following it will be assumed that all vertices, edges and subrequests are enumerated. Numeric values $1, 2, \ldots, N$ will be used to address vertices, $1, 2, \ldots, M$ to address edges and $1, 2, \ldots, R$ to address subrequests. If the request $r$ was divided into subrequests $s_1, s_2 \ldots, s_c$, and the sets of steps $T_1, T_2 \ldots T_c$ were assigned for these subrequests the virtual channel will be formed by the union $\bigcup\limits_{i=1}^{c} T_i$ of steps. In the following the same index $r$ may be used to either address the subrequest, or the virtual channel that was created for the request the subrequest $r$ was built for.

Finally, let the matrix $H = \{h_{fe}\} \in \{0, 1, \ldots, T\}^{R \times M}$ be the schedule: if $h_{fe}$ is non-zero, the virtual channel $f$ will be transmitted over the link $e = (i, j)$ in the time step $h_{fe}$. Otherwise, the link $e$ is not used to transmit the virtual channel.

Let the virtual channel of the subrequest $r$ being transmitted through the path $\phi_r = v_0, v_1, \ldots, v_{N_r} = D_r$ and $e_{m-1} = (k, i), e_m = (i, j)$. Then the delay on the m-th hop may be found as

$$l_{r,m} = \begin{cases} h_{r,e_m} - h_{r,e_{m-1}} & , h_{r,e_m} > h_{r,e_{m-1}} \\ T + h_{r,e_m} - h_{r,e_{m-1}} & , h_{r,e_m} < h_{r,e_{m-1}} \end{cases}$$

The total path delay $L_r$ can be found as a sum $L_r = \sum\limits_{k=1}^{N_r} l_{r,k}$. The problem of minimal delay scheduling can be formulated as a problem of finding the matrix $H : \max\limits_{r \in \{1,2,\ldots,R\}} L_r \to min.$

### 4.2 Problem Formulation

The problem of building the multipath delay-optimal schedule will be formulated as an integer linear program (ILP). The program is built with the following variables:

- $x^r_{i,j}$ is a binary variable that is assigned 1 iff the virtual channel $r$ is being transmitted over the link $(i,j)$ where $i,j=\overline{1,N}, r=\overline{1,R}$;
- $y^r_i$ is a binary variable that is assigned 1 iff the node $i$ receives the data of the virtual channel $r$ where $i=\overline{1,N}, r=\overline{1,R}$;
- $u^{r,t}_{i,j}$ is the binary variable that is assigned 1, iff the virtual channel $r$ is being scheduled to transmit over the link $(i,j)$ in the step $t$ where $i,j=\overline{1,N}, r=\overline{1,R}, t=\overline{1,T}$;
- $b^r_{i,j}=\overline{1,T}$ is an integer variable holding the step number in which the link $i,j$ is scheduled to transmit the virtual channel $r$ where $i,j=\overline{1,N}, r=\overline{1,R}$;
- $p^r_i$ is a binary variable that is assigned 1 if the node $v$ is scheduled to transmit the virtual channel $r$ prior to receive it, i.e. the inversion takes place at the node $v$. Here $i=\overline{1,N}, r=\overline{1,R}$;
- $q^r_i$ is a binary variable that is assigned 1 iff the node $v$ is scheduled to transmit the virtual channel $r$ prior to receive it, i.e. the inversion takes place at the node $v$. If the node $v$ doesn't transmit the virtual channel $r$, this variable will be assigned 0. Here $i=\overline{1,N}, r=\overline{1,R}$;
- $w^{-r}$ is the step that is scheduled for the virtual channel $r$ source to transmit it where $r=\overline{1,R}$ ;
- $w^{+r}$ is the step that is scheduled for the virtual channel $r$ sink to receive it where $r=\overline{1,R}$;
- $a^r$ is an integer variable that is assigned the number of iversions occuring on the virtual channel path. It is obvious that no inversion may take place at the source or at the sink. Here $r=\overline{1,R}$;
- $l_r$ is an integer variable holding the accumulated delay of the virtual channel $r$ where $r=\overline{1,R}$;
- $L$ - the delay upper bound.

**Paths unique and existence constraints:**

**P1:** $\forall r=\overline{1,R}\ \forall i=\overline{1,N},\ i\neq S_r, D_r : \sum\limits_{j=1}^{N} x^r_{i,j} = \sum\limits_{k=1}^{N} x^r_{k,i}$ is the flow conservation constraint;

**P2:** $\forall r=\overline{1,R}\ \forall i=\overline{1,N} : \sum\limits_{j=1}^{N} x^r_{i,j} \leq 1$ is the outgoing flow value constraint. Taking into account **M1** the same constraint will appear to the input flow value.

**P3:** $\forall r=\overline{1,R} : \sum\limits_{j=1}^{N} x^r_{S_r,j} > \sum\limits_{k=1}^{N} x^r_{k,S_r}$ is the source node flow value, must be positive.

**P4:** $\forall r=\overline{1,R} : \sum\limits_{k=1}^{N} x^r_{k,D_r} > \sum\limits_{j=1}^{N} x^r_{D_r,j}$ is the sink node flow value, must be negative.

**P5:** $\forall r = \overline{1,R}\ \forall i,j = \overline{1,N} : x^r_{i,j} \leq c_{ij}$ is a pair of nodes may be scheduled iff the nodes are connected.

**P6:** $\forall r = \overline{1,R}, \forall i = \overline{1,N} : y^r_i = \sum_{k=1}^{N} x^r_{k,i}$ is the variable is assigned 1 iff any incoming edge of the given node in the given slot is scheduled for transmission.

**Steps assignment constraints:**

**A1:** $\forall r = \overline{1,R}, \forall i,j = \overline{1,N} : \sum_{t=1}^{T} u^{r,t}_{i,j} = x^r_{i,j}$ is any link and any request is being scheduled only if the given link was selected to transmit the flow for the given request.

**A2:** $\forall t = \overline{1,T}, \forall i,j = \overline{1,N} : \sum_{r=1}^{R} u^{r,t}_{i,j} \leq 1$ is any link at any step may transmit one flow at most.

**A3:** $\forall t = \overline{1,T}, \forall i = \overline{1,N} : \sum_{r=1}^{R} \sum_{j=1}^{N} u^{r,t}_{i,j} \leq 1$ is any node at any step may transmit via one link at most.

**A4:** $\forall t = \overline{1,T}, \forall i = \overline{1,N} : \sum_{r=1}^{R} \sum_{k=1}^{N} u^{r,t}_{k,i} \leq 1$ is any node at any step may receive the data via one link at most.

**Delays computation constraints:**

**D1:** $\forall r = \overline{1,R}, \forall i,j = \overline{1,N} : \sum_{t=1}^{T} t u^{r,t}_{i,j} = b^r_{i,j}$ is the step number in the schedule. May take values $1, 2 \ldots T$.

**D2:** $\forall r = \overline{1,R}, \forall i = \overline{1,N} : \sum_{k=1}^{N} b^r_{k,i} \leq T p^r_i + \sum_{j=1}^{N} b^r_{i,j}$. If an inversion during transmitting the flow $r$ in the intermediate node $i$ takes place, the variable $p^r_i$ will be assigned 1.

**D3:** $\forall r = \overline{1,R}, \forall i = \overline{1,N} : q^r_i = y^r_i p^r_i$. The variable is assigned 1 if an inversion at the node $i$ takes place and the flow is being transmitted through that node.

**D4:** $\forall r = \overline{1,R} : a^r = \sum_{i=1}^{N} q^r_i$ is the upper bound on the number of inversions appearing during transmitting the flow $r$.

**D5:** $\forall r = \overline{1,R} : w^{-r} = \sum_{j=1}^{N} b^r_{S_r,j}$ is the step number when the flow source sends it.

**D6:** $\forall r = \overline{1,R} : w^{+r} = \sum_{k=1}^{N} b^r_{k,D_r} + T a^r$ is the upper bound on the step number when the flow sink receives it.

**D7:** $\forall r = \overline{1,R} : l^r = w^{+r} - w^{-r}$ is the upper bound on the accumulated delay through the path of the flow $r$.

**D8:** $\forall r = \overline{1,R} : L \geq l^r$ for computing $L$ as the upper bound of the set $\{l^r : r = \overline{1,R}\}$.

The constraint **D3** uses the binary variables multiplication. To linearize the constraint it may be equally transformed into the two linear constraints:

**D3.1:** $\forall r = \overline{1,R}, \forall i = \overline{1,N} : y_i^r + p_i^r - q_i^r \leq 1$
**D3.2:** $\forall r = \overline{1,R}, \forall i = \overline{1,N} : -y_i^r - p_i^r + 2q_i^r \leq 0$
Finally, the integer linear minimization problem can be formulated:

$$L_0 = \min_{\substack{P1-P6\\A1-A4\\D1-D8}} L$$

### 4.3 Heuristic Scheduling Algorithm

To solve the minimum-delay scheduling problem in an efficient way, the heuristic algorithm was developed. The algorithm works fast enough and is easy to implement. The algorithm is based on Dijkstra routing [18] utilizing a very specific way to find the edges weights.

Let $IsFree(n : Integer, u : Node, v : Node) : Boolean$ be the function returning $True$ if and only if the step $n$ is not scheduled yet for the link $(u, v)$.

The function $NearestStep(s : Integer, u : Node, v : Node)$ returns the step number $n$ that is the closest one to the step $s$ in the future and $IsFree(n, u, v) = True$. If there is no free steps for the given link the function returns $NIL$. To simplify the computations, all functions using step numbers are assumed to operate with $(\mathbf{mod}\, T)$: step numbers $s$, $s+T$, $s+2T$, ... address the same step. Using this assumption, the function $NearestSteps(s, u, v)$ is always expected to return either $NIL$, or the value greater then its first argument value $s$.

Finally, let $w$ be the array of weights (this type will be denoted as $Weights$ below), as expected by Dijkstra algorithm. In the developed metric weight has the semantic of the step number at which the node receives the flow: if $w[v] < \infty$ the node $v$ is scheduled to transmit the flow that is currently routed at the step $w[v](\mathbf{mod}\, T)$.

The relaxation $DelayRelax(linkSrc : Node, linkDst : Node, w : Weights)$ function used in the Dijkstra routing algorithm works as follows:

**Input**: $linkSrc$, $linkDst$, $w$
**Result**: the nearest empty slot offset or $NIL$
$n \leftarrow nearestStep(w[linkSrc], linkSrc, linkDst)$;
**if** $n \neq NIL$ **then**
  **return** $n$
**else**
  **return** $NIL$
**end**

To describe the algorithm we also need to define several additional functions:

- Let $DijkstraDelayRoute(s : Node, d : Node, w : Weights) : Path$ be the Dijkstra algorithm implementation using $DelayRelax()$ function instead of default $Relax()$, and returning the path with the minimal possible delay.
- The function $Schedule(path : Path, w : Weight, subreq : Subrequest)$ writes into the current schedule that each link $l = (u, v) \in path$ is being set to transmit the flow for the subrequest $subreq$ in the step $w[l.v](\mathbf{mod}\, T)$.

– The function $InitializeWeights(netw : NetworkGraph, source : Node, w : Weights)$ initializes the weights array by writing $w[v] \leftarrow \infty$ for all $v \neq source$, and $w[source] \leftarrow 0$.

To this end, the scheduling algorithm $DijkstraDelaySchedule(R : Requests, G : Network)$ can be defined:

```
Input: reqs : Set of Requests, netw : NetworkGraph
Data: subs : Array of Subrequests
Data: path : Path in the network graph
Data: w : Weights array
subs ← BuildSubrequests(r);
Sort(subs);
foreach subreq ∈ subs do
    InitializeWieghts(netw, subreq.source, w);
    path ← DijkstraDelayRoute(subreq.source, subreq.destination, w);
    if path ≠ NULL then
        Schedule(path, w, subreq);
    end
end
```

The subrequests array created on the first step is being sorted at the step two via function $Sort(s)$ call. The subrequests may be ordered with different strategies, but the default one is to put the subrequests built from the requests with a bigger capacity prior to the subrequests of the requests with a smaller capacity.

The algorithm is simple and achieves good delay results, which was proved by the simulation. A useful side effect is the increased load balancing: a large flow may be scheduled over several distinct paths, so when the network load increases the paths become longer, covering the nodes those were not used before. The simulation also proves that the under very heavy load the station service ratio may even be very close to 1.

### 4.4 Simulation

To analyze the performance of the $DijkstraDelaySchedule()$ algorithm the simulation experiment was built. The simulation was performed over the network sizes ranging from 10 to 1000 nodes with randomly generated virtual channels requests uniformly distributed over the whole network. During the experiment the data rate was limited by 1666 Mbps. As the first four steps in each 10-step slot were used for the uniform neighbours access (as described above), multi-hop scheduling algorithm was able to use 60 % of the time and consequently ≈1000 Mbps.

The number of virtual channels requests is varied from 1 to 600 for the network consisting of 100 stations, each of them required 100 Mbps capacity (consequently the requested network throughput varied from 100 Mbps to 60 Gbps). The average path length is 3.5 hops in all the experiments. One may observe that under these conditions the total required network capacity is varied up to

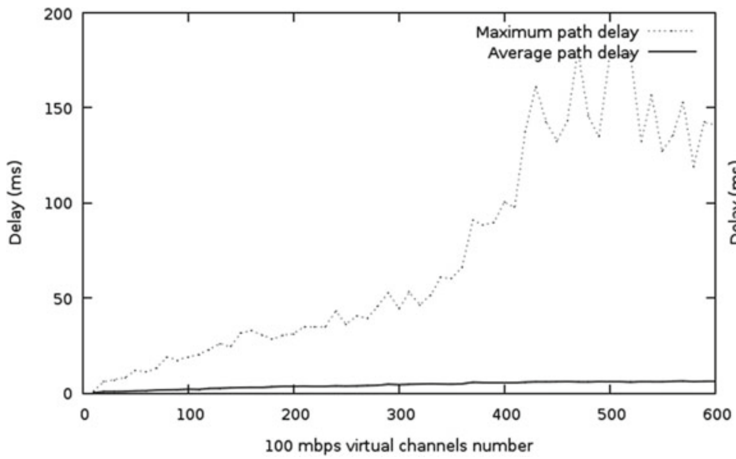


**Fig. 4.** Average and maximum path delay in ms against the number of 100 mbit 3-hops virtual channels requests.

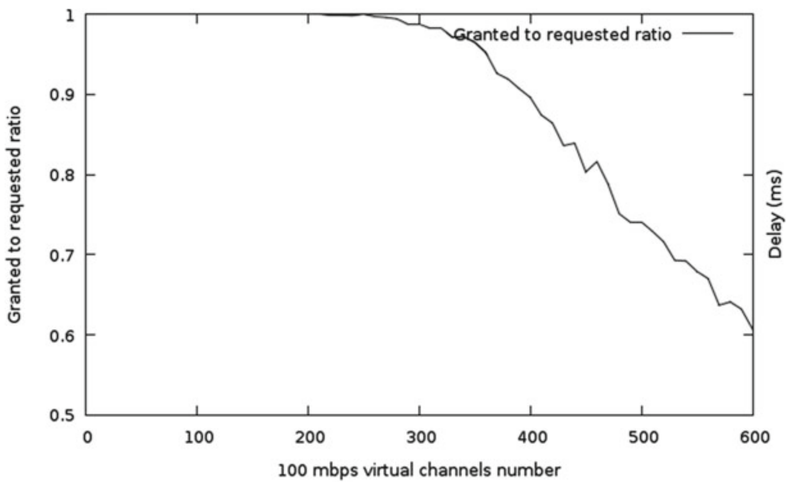


**Fig. 5.** Average granted capacity to the requested ratio.

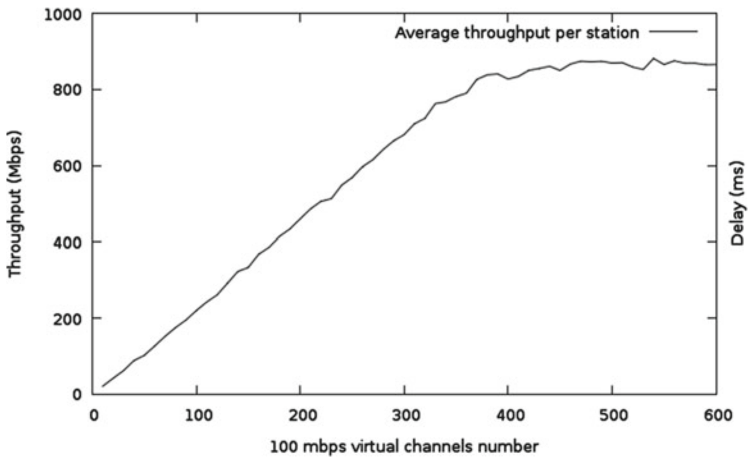


**Fig. 6.** Average base station throughput.

$2100 = 600 \times 3.5$ Mbps per station which is more then 1000 Mbps (the capacity the station may provide for virtual channels transmission). It is possible to schedule most of the virtual channels till the number of requests exceeds 300. Afterwards the ratio of the granted capacity to the requested one downgrades, see Fig. 5. The average and maximum delays are illustrated in Fig. 4. It can be noted that while the maximum delay of a single path may become rather large, the average path delay is still small enough to provide sufficient QoS for VoIP and other delay-critical applications. As each virtual channel contains several paths, the average virtual channel delay may be lower then its maximum path delay. Meanwhile the average throughput per base station is growing along with the requests number and reaches 870 Mbps achieving 87 % of the possible network throughput, see Fig. 6.

## 5 Conclusion

The paper outlined the key features of the emerging mm-wave mesh networks. The networks may be used as the backbones in 4G and 5G networks as well as standalone LAN and MAN networks supporting mobility, QoS, ultra-high throughput and providing high reliability and scalability. These networks may overcome traditional wireless networks in sense of throughput, scalability and reliability providing up to 10 Gbps data transmission rate over large distances.

The network design, primary MAC layer services and Spatial TDMA implementation were discussed. The delay minimizing multihop virtual channels scheduling problem was formulated as the integer linear program. The simple heuristic scheduling method based on Dijkstra algorithm allowing to route each virtual channel via multiple paths and minimizing the delays was presented. Finally, the simulation results proving the algorithm allows providing sufficient delays under very heavy load in large networks were given.

## References

1. Vishnevsky, V., Semenova, O.: Polling Systems: Theory and Applications for Broadband Wireless Networks, p. 317. LAMBERT Academic Publishing, London (2012)
2. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications. IEEE P802.11-2012. IEEE (2012)
3. Ecma/TC48/2010/025. ECMA-387 2nd Edition: High Rate 60GHz PHY, MAC and HDMI PAL. Whitepaper. Ecma International (2010)
4. Pitsiladis, G.T., Panagopoulos, A.D., Constantinou, P.: Improving connectivity in indoor millimeter wave wireless networks using diversity reception. In: 6th European Conference on Antennas and Propagation (EUCAP), pp. 510–514, Prague (2012)
5. Jabbar, J.P., Rohrer, V.S., Frost, J.P.G.: Sterbenz.: Survivable millimeter-wave mesh networks. Comput. Commun. **34**(16), 1942–1955 (2011). ISSN 0140–3664
6. Xiao, S.-Q., et al.: Millimeter Wave Technology in Wireless PAN, LAN, and MAN. CRC Press, Boca Raton (2008)
7. Nelson, R., Kleinrock, L.: Spatial TDMA: a collision-free multihop channel access protocol. IEEE Trans. Commun. **33**, 934–944 (1985)
8. Ronasi, K., Wong, V.W.S., Gopalakrishnan, S.: Distributed scheduling in multihop wireless networks with maxmin fairness provisioning. IEEE Trans. Wireless Commun. **11**(5), 1753–1763 (2012)
9. Chaporkar, P., Kar, K., Luo, X., Sarkar, S.: Throughput and fairness guarantees through maximal scheduling in wireless networks. IEEE Trans. Inf. Theory **54**(2), 572–594 (2008)
10. Djukic, P., Valaee, S.: Link scheduling for minimum delay in spatial re-use TDMA. In: 26th IEEE International Conference on Computer Communications (INFOCOM'2007), pp. 28–36 (2007)
11. Djukic, P., Valaee, S.: Delay aware link scheduling for multi-hop tdma wireless networks. IEEE/ACM Trans. Networking **17**(3), 870–883 (2009)
12. Vishnevsky, V., Larionov, A.: Novel approach for scheduling in STDMA for high-throughput backbone wireless mesh networks operating within 60-80 GHz. In: International Conference on Advances in Mesh Networks (MESH'2010), Venice/Mestre, Italy (2010)
13. Vishnevsky, V., Larionov, A.: GWM-MAC protocol for high-throughput backbone wireless mesh networks operating within 60-80 GHz. In: IEEE International Congress on Ultra Modern Telecommunications and Control Systems (ICUMT'2010), Moscow (2010)
14. IEEE Standard for Local and metropolian area networks. Media Access Control (MAC) Bridges, IEEE 802.1D-2004, IEEE Std. (2004)
15. Moy, J.: OSPF Version 2, IETF RFC 2328 (1998)
16. Clausen, T., Jacquet, P.: Optimized Link State Routing Protocol (OLSR), IETF RFC 3626 (2003)
17. Perkins, C., Belding-Royer, E., Das, S.: Ad hoc On-Demand Distance Vector (AODV) Routing. RFC 3561, IETF (2003)
18. Cormen, T.H., Leiserson, C.E., Rivest, R.L., Stein, C.: Introduction to Algorithms, 3rd edn. MIT Press, Cambridge (2009)

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