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LOAD BALANCING IN TREE-BASED IP MICRO-MOBILITY DOMAINS

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Abstract

Nowadays the penetration of wireless access is continuously increasing. Additionally, the mobile users become more and more dependent on data. The IP-based (Internet Protocol) Internet was designed for data transmission and has become the most ubiquitous wired internetwork. According to these trends the next generation networks (and already 3G networks also include IP-based parts) are designed as a combination of these two types of networks (mobile and IP-based). The Mobile IP protocol handles mobility in the IP layer globally, but it is not well-adopted to local coverage areas. Within such access networks the micro-mobility proposals enhance the performance of Mobile IP. In this paper we propose a solution for improving the performance of tree-based micro-mobility protocols by rearranging their capacity using additional links. Based on analytical considerations we obtain a formula to determine the optimal link size in particular cases. The method is also examined with our simulation testbed, the results show improvement in the performance of the domain.

Keywords: telecommunication, IP mobility, micro-mobility, load balancing, alternative links.

1. Introduction

Nowadays the penetration of wireless access is continuously increasing. Additionally, the mobile users become more and more dependent on data (e.g. real-time media streaming, web browsing other interactive traffic). Often mentioned keywords are ubiquitous and pervasive computing, anytime and anywhere network access. Wireless networks were designed for voice transmission in the beginning but now are also used to forward data. Parallel to the evolution of mobile systems the number of Internet subscribers also has risen exponentially. The IP-based (Internet Protocol) Internet was designed to transmit data instead of voice between wired hosts and has become the most ubiquitous wired internetwork. According to these trends the next generation networks (and already 3G networks [18] also include IP-based parts) are designed as a combination of these two types of networks (mobile and IP-based) [14]. Probably the Internet Protocol will be applied end to end and will support mobility in the same network layer. Therefore it seems to be worth to implement the mobility management in the network layer, namely in the Internet Protocol. IETF (Internet Engineering Task Force) is working on the problem, the solution is called Mobile IP; for IPv6 and IPv4 it is defined in [7] and [15], respectively. In this article we focus on IPv6 [4] and its extensions.

This paper is organized as follows. In Section 2 we introduce IP mobility, both macro- and micro-mobility. Section 3 is about our proposed extension to tree-based micro-mobility domains. In Sections 4 and 5 we show our analytical and simulation results, respectively.

2. IP Mobility

Mobile IP is designed to allow mobile hosts to remain reachable while moving around in the Internet. This means continuous availability also during the handover (change of attachment points to the network), so that no upper layer connections need to be reestablished after connecting to a new access point. The origin of the problem with mobility in IP networks is that the IP addressing scheme is hierarchical based on certain length prefixes [4]. With handovers the IP address of mobile nodes must be changed, because the address itself identifies the location of the host in the network topology. This temporary address varying with handovers is called care-of address in Mobile IP. From the Mobile IP's point of view only third layer (L3) handovers have to be considered. With the change of this address the ongoing connections would be disrupted in the basic Internet Protocol, but with Mobile IP these handovers can be hidden from upper layers.

On the other hand a fixed address (called home address) is needed that can be used to identify the mobile host itself independently from its current location. Because communication partners (correspondent nodes) will only be able to reach the mobile host if they can address it. A simple solution is that these fixed addresses should be valid IP addresses, so packets with such a destination address will be forwarded to that particular subnet. To forward these packets to their final destination, i.e. the care-of address, an entity (home agent) is placed in the subnet of the home address (called home network) that intercepts packets and tunnels them to the mobile (being in a foreign network). The connection between the two addresses (called binding) is stored in the home agent located in the mobile host's home network. The mobile node has to send signalling packets (binding updates) to refresh or create the binding. Bindings can be stored in all Mobile IPv6-capable nodes. Mobil IP also provides security mechanisms that aim to authentication and authorization of mobile and correspondent nodes

Mobile IP handles mobility globally, but its performance can be improved. If the foreign network to which the mobile node is currently attached to is far away from the home network or from a correspondent node, the propagation delay of binding update messages can be relatively high. This can cause increased packet loss. Several applications may need stronger requirements, e.g. lower packet loss and shorter interruption of communication (blackout) during handovers.

In wireless networks the bandwidth is a very limited resource. The increasing density of mobile users results in higher bandwidth needs. They can be served by using smaller radio cells; by that frequency reuse will be possible within smaller areas. Thus, the same frequency band can be used more times and the total provided capacity will be higher, compared to the case of larger cells. Transmission rate over radio channels also depends on the velocity and distance of communicating peers. Higher rate is possible if peers are closer to each other. Based on these facts future cellular networks, especially in hot-spots where a lot of users are communicating simultaneously, will use smaller radio cells in order to provide high speed network access for higher number of users. But these smaller cells will cause more frequent handovers, which will load the network with a lot of mobility management messages.

2.1. Micro-Mobility Protocols

To handle the above-mentioned problems there can be found several micro-mobility proposals in the literature, providing fast, seamless and local handover control in limited geographical areas by introducing hierarchy in the mobility management architecture. They can achieve smaller handover latency and can also decrease the amount of signaling for the whole Internet, because a part of it will only affect the local micro-mobility domain. They usually have paging support [8], which is designed in support of scalability and saving accumulators' power. These solutions extend the basic Mobile IP protocol locally, inside a well-defined geographical area using new local network entities. They can be considered a special access network from Mobile IP point of view because they hide the movements of mobile hosts moving within such a micro-mobility domain from the global Mobile IP. When applying these protocols binding updates to home agent and correspondent nodes must only be transmitted when handover is performed between different micro-mobility domains. As long as a mobile is staying within the same micro-mobility domain it only has to register the change in L3 attachment points with local entities, which is faster than signalling through the whole Internet. In general, the principal entity of these protocols is a gateway, which implements the connection between the Internet and the local access network. It receives packets destined to mobile hosts in its domain and forwards them to their destination based on location information database created by local registrations. The relation between macro- and micro-mobility and the typical architecture of micro-mobility domains can be seen in *Fig. 1.* In the followings, we survey micro-mobility proposals, focusing on tree-based solutions.

A *Cellular IP* (CIP) [19] domain consists of several CIP routers placed in the nodes of a tree graph. The leaves are base stations that are responsible for transmitting the packets to the mobile hosts via the air interface. At the root of the tree there is a gateway router that connects the micro-mobility domain to the (Mobile IPv6-capable) global internet. The routers know the exact location of the mobile, they store an outgoing downlink interface identifier for each mobile. In

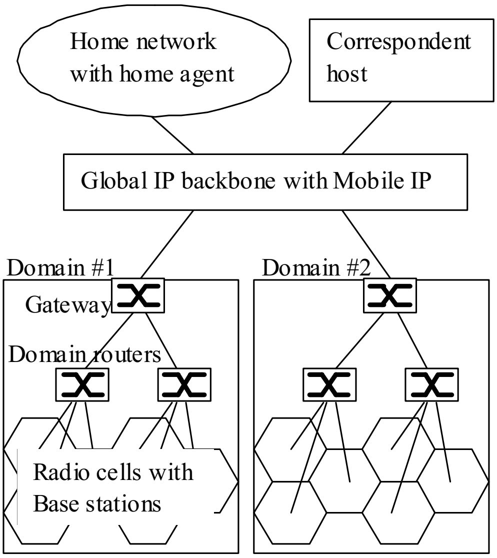

Fig. 1. Architecture of a Mobile IP network with micro-mobility support

the case of idle mobile hosts not all routers of the domain store information about the position of the mobile host. Below these the domain cannot do anything but broadcast the packet to each radio cell. This area is called paging area. Whenever an idle mobile host gets a packet it must register its exact location with a route update message. Mobiles and domain entities must be aware of the Cellular IP protocol, but outside the domain it operates transparently.

Cellular IP supports two types of handover scheme. Hard handover is based on a simple approach that trades off some packet loss in exchange for minimizing handover signalling. Semi-soft handover prepares handover by proactively notifying the new access point before actual handover.

To minimize control messaging, regular data packets transmitted by mobile hosts are used to refresh host location information. So Cellular IP uses mobile-originated data packets to maintain reverse path routes. Routers monitor mobile originated packets and maintain a hop-by-hop location data base that is used to route packets to mobile hosts. The entries are stored soft-state, i.e. they expire after a certain amount of time or have to be refreshed periodically. Cellular IP tracks the location of idle hosts which do not have to update their locations after each handover. When packets need to be sent to an idle mobile host, the host is paged using a limited scope broadcast message.

A *HAWAII* (Handoff Aware Wireless Access Internet Infrastructure) [16] domain comprises several routers and base stations running the HAWAII protocol. A mobile host in a HAWAII environment runs a standard Mobile IP protocol engine with Network Access Identifier, route optimization and challenge/response extensions. The gateway is called domain root router. HAWAII uses three types of path setup messages: power-up, update and refresh. On power up a mobile host sends a Mobile IP registration request message to the corresponding base station. The base station then sends a HAWAII path setup power-up message to the domain root router which is processed in a hop-by-hop manner. In all routers on its way to the domain root router this power-up message adds a routing entry for the concerned mobile host. The domain root router acknowledges this path setup power-up message to the base station which notifies the mobile host with a Mobile IP registration reply.

Another example for these protocols is IETF's *Hierarchical Mobile IP* [17], which extends Mobile IP with a similar mechanism to handle mobility locally. The new entity is called Mobility Anchor Point (MAP) that acts as a local home agent. The mobile host registers its interface's address with the MAP, and registers another address with the home agent. Packets destined to this latter will be intercepted by the MAP and forwarded to the mobile node. This solution needs no micro-mobility specific domain, it uses basic IP routing, only an additional entry (MAP) is used.

There are also further proposals, for example TeleMIP [3] performs load balancing in a Hierarchical Mobile IP-like architecture to share the registration load on local agents. Regional Registrations [12] use local tree-topology extensions to the basic Mobile IP similar to the approaches above. Ad-hoc routing protocols [9] usually perform reactive routing, which locates mobiles on-demand. Proactive algorithms maintain information about the topology and location of hosts, which have to be refreshed periodically. Another way to improve the Mobil IP is presented in [10], which establishes a tunnel before the handover based on L2 triggers and uses it while L3 handover finishes.

So there are differences between micro-mobility proposals. Some of them provide some kinds of paging – a support for idle (currently not communicating mobile hosts) [5]. Hierarchical Mobile IP makes use of the basic IP routing. Others use their own routers organized in a tree topology, like Cellular IP, Regional Registrations or HAWAII. According to these proposals the routing in a micro-mobility domain is performed in a hop-by-hop manner, states in routers are refreshed by local update signalling. All micro-mobility protocols maintain a location database that maps mobile host identifiers to location information to ensure that packets arriving from the Internet and addressed to mobile hosts are forwarded to the appropriate wireless access point in an efficient manner.

3. Improving the Performance with Capacity Rearrangement

3.1. Motivation

Several types of data traffic, like real-time multimedia transmissions (e.g. video conferencing) do not tolerate high packet losses, delays or delay variation. These factors should be kept as low as possible by designing network more and more efficient. As was presented above, there are several tree-based micro-mobility proposals, in which inside the domain packets are routed based on individual addresses or cache entries for each mobile host. Others make use of basic IP routing for tunnelling packets between the mobile and the gateway entities, for instance in Hierarchical Mobile IP. In this article we are dealing with the first group, i.e. with protocols that use their own routing methods. In this group routers are typically organized into a tree topology to deliver packets to the mobiles. We propose a solution to make these protocols more effective.

Two main reasons can cause high packet losses and delays in the IP layer. First, tree nodes are single points of failures, whichever fails its child nodes will lose its network access. If the gateway fails, the whole domain will be disconnected from the backbone network. The gateway being a single point of failure is a common problem in micro-mobility solutions. Not only network failures but also congestion can lead to packet losses or high propagation delays. If mobile users move in large groups, they can overload certain parts of the network. This user-group can be for instance a crowd leaving after an event like a conference or a sport event. Several users of a cell transmitting at too high data rates can have similar effects. Besides, the domain may have less utilized parts, which could be used to transfer packets. If so, they could somehow be used to forward those packets that would be lost in the congested part.

In this article we propose and analyse a solution to improve the performance of such tree-based micro-mobility domains by adding alternative links to the basic tree topology. This solution aims to enhance the sharing of resources and also improves the robustness of intermediate nodes of the tree; only the gateway remains to be a single point of failure. To make the solution work we combine local mobility location update messages with a load balancing scheme, with which we can eliminate the need for additional signalling in the domain. With micro-mobility protocols that use their own routing algorithm, alternate paths and propagating mobility management messages also along them (so integrating load balancing and mobility management) make sense similar to [2]. With pure Hierarchical Mobile IPv6, which applies IP routing, the registration messages could be forwarded along an alternate route, but this load balancing will be independent from mobility. In the former case with this solution we integrate the mobility management and the routing with load balancing functionalities, but HMIP's update messages do not care about the path along which they have reached the gateway entity, they are only processed in the Mobility Anchor Point. After this point we will focus on tree-based micro-mobility protocols.

3.2. *Alternative Links*

Our solution makes the following assumptions about the IP micro-mobility domain. It contains a gateway entity that connects the domain to the global Internet and several router entities organized in a hierarchical manner. In the leaves of the router-tree, the base stations are responsible for signal transmission to the mobile devices over the radio channel. The routing information is created and refreshed by location update (registration) messages that maintain the states for mobiles in micro-mobility domain's routers. These messages correspond to the mobile IP's binding update but these work in a local environment. Routing is performed based on these entries to the appropriate downlink neighbour downwards and to a default uplink neighbour upwards. So the location information of each mobile host is stored in all routers along the path between the gateway and the certain base station the mobile is currently attached to. These entries tell the router, which downlink interface it shall use in order to reach the mobile. The entries are stored soft-state; it means they expire after a certain amount of time. They must be created or refreshed periodically by the mobile host by sending location update messages. Packets (also registration messages) from the mobile are forwarded to the default uplink neighbour in a hop-by-hop manner until the gateway. During this transmission registration messages create/refresh router entries for that particular mobile host. According to these assumptions, by applying this solution several modifications may be needed with micro-mobility protocols. For example in Cellular IP the data packet should not refresh location information but the update messages instead; and the routers of the protocol should be prepared to handle alternative links, and multiplying registration messages along them.

Whenever a router receives too many packets it will drop them above its capacity. The principal idea of our solution is to use also the less loaded routers of the domain in the case of congestion (load balancing). To achieve this, we extend the micro-mobility domain's router tree with alternative routes (additional links). In *Fig. 2.* they are represented by dashed lines (l_7, l_8 and l_9). These links mean additional connections beside the branches of the tree, which will be used in a case of failure or congestion. So we can split the traffic among these routes if there is not enough capacity somewhere in the domain. And as it is commonly known, sharing resources is essential for achieving better QoS (e.g in [1]). If a queue of a router's outgoing interface is full then the router will forward the incoming packet to an alternative route (link). The expected advantage of this solution is the effective utilization of network resources and eliminating single point of failures from the inside of the domain (gateway still remains such point).

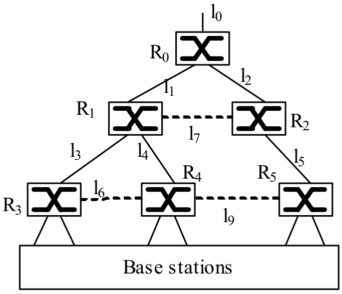

Fig. 2. A sample domain with alternative links

3.3. Packet Forwarding

When a packet has to be forwarded upwards (from a mobile host in the micromobility domain through the domain's gateway to any correspondent host), the router which has a congested default outgoing interface, can forward the packet along an additional link towards one of its neighbours. In the opposite direction (from the gateway to a mobile in the domain) the packets cannot be routed to an alternative path because there is no information about the location of the mobile host, so the packet will be lost or broadcasted. Multiplying location management messages can solve this problem. Whenever a mobile host sends a location update (e.g. route-update or paging-update), a router with alternate links must send this message to several routes. If we maintain additional entries in routing caches of routers in the alternative route it will be possible to use this when there is a demand for an alternative way in the downlink direction. These entries do not play any role when there is no congestion or failures in the downlink direction. On the other hand it does not differ from 'normal' route-update entries in any route caches. It is important to maintain also this entry with the default route's entry because congestion can begin at any time and after that we have no tool to search for a route (except broadcasting, but this is not a proper method by congestion, because it largely increases the load, so decreases performance of the network).

This solution still does not handle inactive hosts, because there is no information about their location in routers. These hosts cannot get any packets until the congestion ends. This event occurs less frequently than the congestion in general (there is an additional condition: inactivity of the mobile host). In this case we could use a broadcast message started at the alternative route of the router before the congestion. There is another way to handle this case: in a congested network the probability of connection interruption (of a real-time connection) or the packet loss is much greater than in a not overloaded network. So it can be a good solution not to allow these mobile to become active. We can extend the Call Admission Control (CAC) algorithm with this condition, which can deny the call at that time so these packets can be dropped. Using alternative routes the CAC algorithm can allow more users below a router than without alternative routes because the traffic has an additional route.

3.4. Discussion

So the topology shall contain additional links to the tree topology. In this domain in the uplink direction routers duplicate registration packets whenever there are multiple uplink routers. This creates multiple downlink paths for each mobile node. The branching factor (how many downlink path is created) can be used for control the registration message load and the amount of backup downward routes in the domain. These paths can all be used when routing downlink packets if the default path is congested. In the uplink direction routers forward packets to the default uplink neighbour, but they can choose another alternative link if congestion or failure is present. The default uplink router mentioned above is determined in the original tree topology, i.e. the parent node of the router in the tree.

By this method these alternative routes are to be used when a normal (tree branch) route currently has not enough capacity and is not able to transmit the packet. So routers' capacity can be smaller for achieving the same QoS, and the traffic on an overloaded branch can be redirected to another branch, where there is more capacity available. Propagating of update messages also along alternate routes has another advantage (in addition to higher throughput and reliability): There will be a path downwards close to the current path to the current attachment point. When a handover occurs the crossover node may be lower in the tree than in the case without these alternate routes. With these alternative links we expect to decrease packet loss. Due to this, less retransmission will be needed in the transport layer, so delay is also expected to be smaller. This works similar to Integrated services and RSVP except that here no resource reservation is carried out, only the path is created and maintained in the domain.

With these added links we can distribute the load over bigger parts of the domain. Thus, we can serve the same load with less of the link's capacity in such sense, because we do not need to have that capacity towards each leaves of the tree. Without additional links the last links (connecting the routers with base stations to the domain) would have to be wide enough to transmit the offered load. The gateway router of the domain is still a bottleneck (also from the viewpoint of reliability: failure in the gateway causes interruption of all connections to the global IP network). It is worth using this algorithm when there is an asymmetry in the network load and additional unused resources are available in the other parts of the network. Inactive mobile hosts are not important because they become active before sending packets or after receiving the first packet. This method can be extended to use resources of the neighbour domain, but packets have to be passed through the original domain's gateway, since the mobile has valid registration only with that.

4. Analytical Model

In this section we will present our results in determining the optimal value of a link between two routers connected to a common upward neighbour. We take the distribution (density function) of the load coming from downwards and the total capacity of the three links as input. Load coming from upwards can be considered in a similar manner but in that case it must be split based on packets' destination address. With the spread of peer-to-peer technologies the up- and downward traffic's characteristic will be similar. The investigated topology can be seen in *Fig. 3*, which is a part of the topology in *Fig. 2*.

Router #0 is the uplink neighbour for routers #1 and #2. Links #1 and #2 are branches of the original router tree; link #3 is an additional link that we use for lad balancing. In this topology we considered the incoming traffic from downwards as a

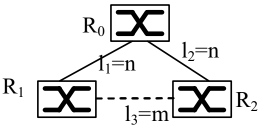

Fig. 3. The examined part of the domain

distribution of the load as a distribution on bandwidth. The question we investigated was, what should be the optimal value for link #3 considering these conditions. For simpler calculations we assumed a symmetric case, so $l_1 = l_2 = n$ and $l_3 = m$, and the load in routers #1 and #2 has the same distribution. These distributions were chosen to be several basic distributions, like uniform, exponential or normal. These distributions represent the load in routers, i.e. tell the probability of a certain kilobit/second load. This traffic arriving in two lower routers must be transmitted to router #0. According to this they should not have non-zero values in the domain below zero. Until the traffic arriving in router #1 fits in link #1 packets will be routed along that link, overflowed part will be routed along link #3. If link #2 has free capacity then this overflowed traffic will reach router #0 through links #3 and #2. This also can be said about router #2. So the bound of transmitted traffic is the capacity of $l_1 + l_2$. The advantage of the additional link is, that the load is asymmetric, e.g. router #1 has higher load than #2. It turns out that moving capacity from tree branches to l_3 will decrease the packet loss, even if $l_1 + l_2 + l_3 = C$ is fixed. Of course if we have an extreme distribution for the traffic this will not be true. For example if the load is $C/2$ for both router #1 and #2, then it makes no sense to move capacity to link #3.

So where we start is: $2n+m = C$ is fixed, we assume some kind of distribution for the load in routers #1 and #2 (independent), and the question is an optimal value for l_3 if it exists. The bivariate distribution that tells the load in both lower routers can be calculated as the product of the two marginal distributions in routers #1 and #2. Certain parts of this two-dimensional space represent packet loss. We determined the area where there is no packet loss, i.e. the traffic can be transmitted either directly on link #1 or #2, or through link #3. Integrating the distribution above the complement of this area will tell us the probability of packet loss in the function of C, m, and distribution's parameter(s). We should find the minimum of this formula in m to get the optimal value for link #3.

In *Fig. 4* we can see the coordinate system above which there is the bivariate distribution. The first axis represents the load in router #1, the second axis in router #2. When $m = 0$ the maximal transmitted traffic is bounded a horizontal and a vertical line at $C/2$. If we begin to increase m, in this rectangle's upper right corner appears a new side bounding the traffic along the link #3. The greater m the closer the sloping side to the origin and the farer the vertical and horizontal line from the origin. If m reaches $C/3$ we get an isosceles right triangle, the equal sides are $2C/3$ length. Above $C/3$ m becomes useless because the rest of capacity for n will be smaller than $C/3$ so traffic transmitted on l_3 is unable to reach router #0. As m increases the area of no packet loss transforms towards this triangle. One step can be seen in *Fig. 4*, where the gray parts appear instead of the hatched part. The x- and y-intercepts of vertical and horizontal lines are $(C+m)/2$, the coordinates of the sloping side are $(C-3m)/2$ and $(C+m)/2$, respectively.

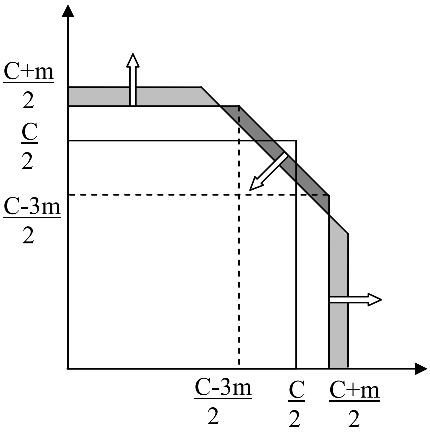

Fig. 4. Behaviour of the area above which the load's distribution has to be integrated

To determine the probability of no packet loss we have to integrate the distribution function above the diagonally hatched area in *Fig. 5*.

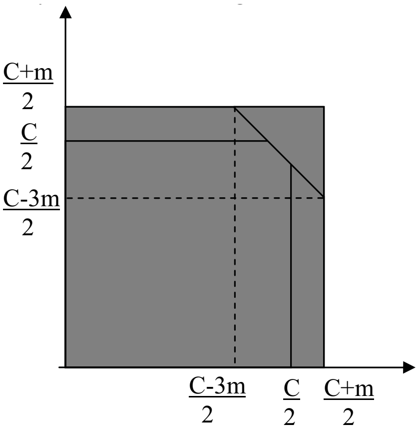

Fig. 5. Area above which the load's distribution has to be integrated

This can be done by the following formula, in which we calculate the integral above the whole square and subtract the integral above the vertically hatched triangle.

$$T = \int_{0}^{(C+m)/2} \int_{0}^{(C+m)/2} f(x, y)\,\mathrm{d}y\,\mathrm{d}x \quad - \int_{(C-3m)/2}^{(C+m)/2} \int_{C-m-x}^{(C+m)/2} f(x, y)\,\mathrm{d}y\,\mathrm{d}x \qquad (1)$$

The probability of packet loss can be determined if we subtract this value from one. Now we evaluate this formula for different distributions and try to find an optimal solution for m if any. So we have to minimize $1 - T$ in m.

4.1. Uniform Distribution

The simplest distribution is the uniform distribution that has uniform values above a rectangle, in a symmetric case between $(a, a) - (a + b, a + b)$ points, so that its integrate is one (value is $1/b^2$). In this case there can be done several restrictions in order to make the optimization task reasonable. Our goal is to decrease the total capacity needed for meeting users requirements (achieve as low packet loss as possible). With the uniform distribution, $C/2 < a + b$ should be satisfied, or else the whole area, where the probability of load is not zero, will be covered without additional links. Of course, providing lossless packet transmission is acceptable for the users, but can be very expensive for providers. So we may decrease the total capacity below $a + b$, but it must be greater than a, or else packet loss probability will be one.

When increasing m, the sloping side will intersect the $(a, a) - (a + b, a + b)$ rectangle sooner or later, because based on the previous assumption ($a < C/2 < a + b$) the upper right vertex of the $C/2$ sided rectangle will start ($m = 0$) from inside the uniform distribution. We can have two cases, when the sloping side reaches the distribution's boundaries. They can be seen in *Fig. 6*.

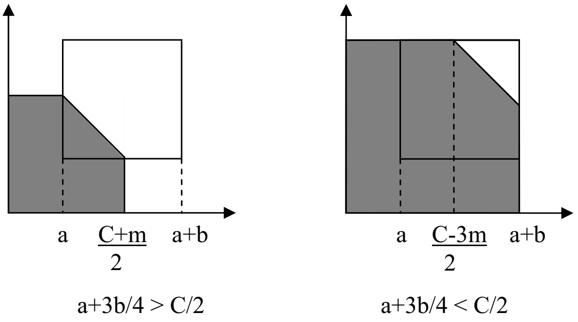

Fig. 6. Two cases, how the sloping side can leave the distribution's area

In the first case the probability of packet loss is always greater then $1/4$ (equation when $m = 0$) because of the constraint for $C/2$. Thus we will consider the second case, where $a + 3b/4 < C/2 < a + b$. When m increases, we have four cases.

- $0 < m < 2a + 2b - C$
- $2a + 2b - C < m < C - (2a + b)$
- $C - (2a + b) < m < C - 2a$
- $C - 2a < m < C/3$

The according figures for the first and second cases can be seen in the first and second coordinate system in *Fig. 7*, respectively. The third figure shows the last two cases, where the hatched area is below the diagonal of the square (above which there is the uniform distribution). Except the first case, the packet loss probability (represented by the not hatched part of the square) increases with m, so the optimal value will be in the first or second cases. Of course if the bounds that separate cases are greater than $C/3$ (i.e. we reach $m = C/3$ before these cases), there may be less different placement of these shapes.

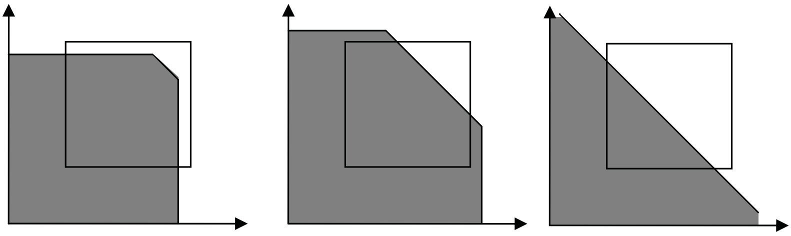

Fig. 7. Cases where the packet loss can be calculated separately

So the optimal value for m must be in the interval $0, 2a + 2b - C$. If we calculate the packet loss probability for that case it gives:

$$\left(a + b - \frac{C + m}{2}\right)\left(\frac{C + m}{2} + b - a\right) + 2m^2, \qquad (2)$$

which is a simple second order polynomial in m. Its minimum is at $m = (C - 2a)/7$. If we calculate the first derivative of the formula above, and evaluate it in $m = 0$, we get $a - C/2$, which is negative because of the constraints. Evaluating it in $m = 2a + 2b - C$, the result is $8(a + 7/8b - C/2)$, which can be either positive or negative. If C is great enough, then it will be negative and optimal value for m will be $m_{\text{opt}} = 2a + 2b - C$. In the other case $m_{\text{opt}} = (c - 2a)/7$.

Until now we determined the optimal (giving minimal packet loss probability) size of the link between two routers connected to a common upward neighbour, assuming that the load's distribution is uniform and independent of each other. There were several cases because of the type of distribution. With others that have a simple analytical form, things become a bit easier, but as it will be seen, we have a closed form for m_{opt} only in few cases.

4.2. Exponential Distribution

First take an exponential distribution, which is not very suitable for modelling the load but it provides a nice closed form solution. The two-dimensional density function is:

$$\lambda^2 \exp\left(-\lambda(x+y)\right) \tag{3}$$

If we calculate (1) for that distribution, we get:

$$1 - T = 2\exp\left(-\lambda(C+m)/2\right) + (2\lambda m - 1)\exp\left(-\lambda(C-m)\right) \tag{4}$$

Of course the $m < C/3$ is still needed. The graph of the formula for $C = 60$ and $\lambda = 1/5$ can be seen in *Fig. 8*.

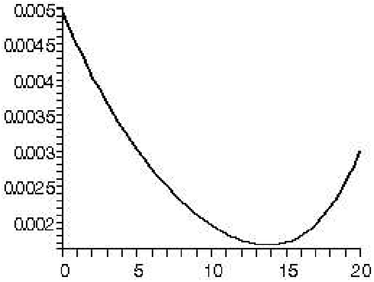

Fig. 8. The packet loss probability

There is a minimum at about 14. To calculate the exact minimum point, we have to differentiate with respect to m, and obtain the root of the formula (where it will be zero), that will be:

$$m_{\text{opt}} = \left(4W\left(\frac{3}{4}\exp\left(\frac{\lambda C}{2} + \frac{3}{4}\right)\right) - 3\right)\Big/(6\lambda), \tag{5}$$

where $W(\cdot)$ is the Lambert W-function (also called the omega function), the inverse of $f(x) = x\exp(-x)$. *Fig. 9* depicts this optimal m_{opt} value, it may seem to be linear in C, but it is not. Only its slope converges to $1/3$.

If we shift the exponential distribution towards positive infinity by a value of k, the formula for m_{opt} will change a bit:

$$m_{\text{opt}} = \left(4W\left(\frac{3}{4}\exp\left(\frac{\lambda C}{2} - \lambda k + \frac{3}{4}\right)\right) - 3\right)\Big/(6\lambda). \tag{6}$$

If we extend the shifted exponential distribution according to *Fig. 10*, we can not obtain a closed form solution for m_{opt}. But the minimum of $1 - T$ still exists and can be determined numerically.

So we could obtain a closed form solution for the exponential distribution, and for a shifted version.

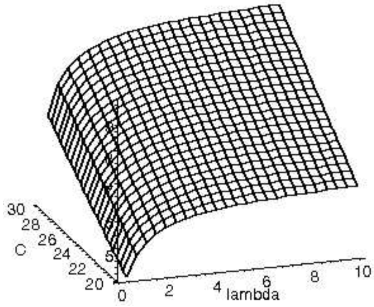

Fig. 9. The optimal value of m

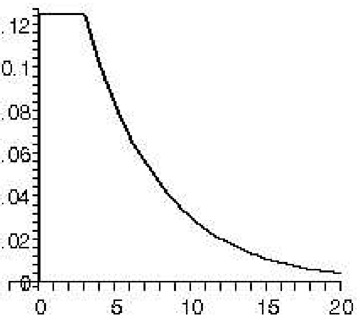

Fig. 10. Density function of shifted and extended exponential distribution

4.3. Normal Distribution

Mobile users' traffic is cumulated in the domain's routers. If we have many users, the sum of independent random variables with a given distribution has a limiting cumulative distribution function according to the central limit theorem. So the traffic of many users may behave as if it were a normal distribution. In the followings we will examine this case; we assume a normal distribution for the load. The normal distribution is given as:

$$f(x) = \frac{1}{\sqrt{2\pi s^2}} \exp\left(-\frac{(x-e)^2}{2s^2}\right), \tag{7}$$

with expectation value e and variance s^2. But these parameters cannot have arbitrary values, because load is always non-negative and the normal distribution allows negative values, too. So this distribution is an approximation, the expectation value must be greater than the standard deviation (s), or even greater to have only a little probability in the negative domain.

If we calculate $1-T$ according to (1) we get a complicated formula with many $\mathrm{erf}(\cdot)$ (error function) addends, containing also integration of $\mathrm{erf}\,(\cdot)$ functions. In this case we could not obtain any closed form solution for m_{opt}. Differentiating the packet loss probability and solve it for m means that, when increasing m, from that optimal point the packet loss probability will increase. In *Fig. 4*, this point is reached when the integration of the two-dimensional normal distribution above the gray area will be equal to that above the hatched area. We will show this approach, which is basically the same as finding the roots of the first derivative. The probability above the gray area by normal distribution is:

$$2\frac{1}{s}f\left(\frac{C+m-2e}{2s}\right)\int\limits_{0}^{(C-3m)/2}\frac{1}{s}f\left(\frac{t-e}{s}\right)\mathrm{d}t, \tag{8}$$

which is the infinitesimal change of the volume above the half of the two gray areas, multiplied by 2. The weighting factor is needed according to the distance from the peak (median) of the distribution. The $1/s$ factors are needed to transform the standard normal f into a normal density function. In a similar manner above the hatched area (in *Fig. 4*):

$$\frac{1}{s}f\left(\frac{C-m-2e}{2\sqrt{2}}\right)\sqrt{2}\int\limits_{e-\sqrt{2}m}^{e+\sqrt{2}m}\frac{1}{s}f\left(\frac{t-e}{s}\right)\mathrm{d}t, \tag{9}$$

where the additional factor (square root of two) is needed because integration is done along a distorted (sloping) line. These two formulas must be equal in order to obtain m_{opt}:

$$\begin{aligned}&\exp\left(-\frac{C^2-6Cm-4Ce+m^2+12me+4e^2}{8s^2}-\ln\sqrt{2}\right)\\&\quad=\int\limits_{0}^{(C-3m)/2}\frac{1}{s}f\left(\frac{t-e}{s}\right)dt\Bigg/\int\limits_{e-\sqrt{2}m}^{e+\sqrt{2}m}\frac{1}{s}f\left(\frac{t-e}{s}\right)\mathrm{d}t.\end{aligned} \tag{10}$$

We should solve this equation for m, but the integration of Gauss functions makes the computation difficult. If we assume that the quotient of the two integrals is approximately constant independent from m, then we can obtain an approximate m_{opt} easily from a second order polynomial. Let q denote the quotient of thee two integrals (right-hand side of (10)). Assuming that q is nearly independent from m (so the right hand side of (10) is constant for a given distribution), the solution for (10) can be written as:

$$m_{\mathrm{opt}}=3(C-2e)-2\sqrt{2(C-2e)^2-s^2\ln 2-2s^2\ln q}., \tag{11}$$

This is the solution from a second order polynomial similar to the argument of the exponential function in (10). The other solution (taking the square root with positive sign) is above the allowed domain of m. We investigated several numerical examples in which the value of m_{opt} could be approximated quite precisely with the solution assuming $q = 1$. Two solutions can be seen in *Fig. 11.* The curves starting in zero below the horizontal line are the quotient of the exponential weighting factors including the square root of 2(so they are Gaussian-like functions, second order polynomial in the exponent), the other two curves show q. The point is that the intersection of the two curve pairs (dashed and solid) are very close to the horizontal line, so we can approximate their intersection with the intersection of the exponential and a constant function, which is must simpler to compute. If the value s increases but not exceeding the bound above, the approximation becomes less precise. ($C = 35$, $e = 15$, $s = 0.5$ (dashed) and 2.35 (solid))

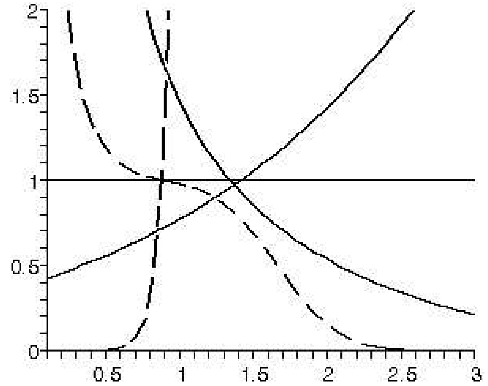

Fig. 11. Two sides of the equation

Both sides of (10) are monotonic, because in q the numerator always decreases, the denominator always increases, maximum of the factors' quotient (left side of (10)) is at $3(c - 2e)$, so the intersection must be before it. This is why the other solution in (11) was irrelevant. With several C and s values the quotient of the two integrals (q) can be seen in *Fig. 12.* Probably the precision of the approximation is related somehow to the ration of $(C - 2e)$ and s as we have mentioned at *Fig. 11*, but this is still part of the future work.

To apply or validate the approximation we can make some restrictions for our parameters considering the meaning of the variables. If we want to keep packet loss below 2.5% then $C/2 - e > s$ must be true because the probability above the infinite rectangle that is always (independent from m) outside of our hatched shape in *Fig. 5* would be too high (above 2.5%).

When $m = 0$, the quotient of the weighting factors is less than one and $q > 1$. If $m = (3 - 8^{1/2})(C - 2e)$ then both q and the quotient of the exponential factors are one, so q is still greater ($2^{1/2}$ times). Above $(C - 2e)/3$ it changes and q will be less, if $s < 8^{1/2}(C/2 - e)/3$. This comes from the point, where the gray area in *Fig. 4* reaches the median of the Gaussian curve, so that the numerator of q becomes less than $1/2$. According to the previous condition the denominator will be greater

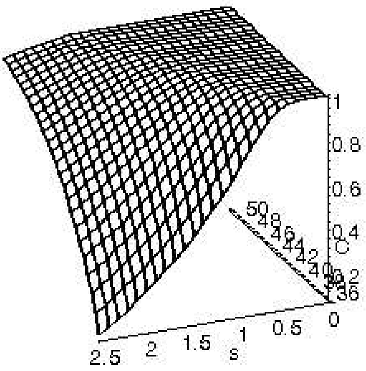

Fig. 12. The quotient of integrals (q), this must be close to 1 to make the approximation exact

than erf $(2^{-1/2})$, so q will be less than 0.74. As both side of (10) is a monotonic function the solution must be between these two bounds, i.e. $0.17(C-2e) < m < 0.33(C-2e)$. So we have a method to estimate the m_{opt}, but the correctness of this method is not proved, only a bound was provided, between that the solution must be.

By increasing m we are trying to find a shape (hatched area in *Fig. 13* below a circular Gaussian function (two-dimensional distribution function for independent normal random variables) with a maximal integral value above it. Of course the packet loss should be reasonable, so $e < C/2$ (the peak of the Gaussian surface is above the initial ($m = 0$) square). If $m > 0$, the peak gets farer from the considered area. So what we are doing with m_{opt} is that we are trying to fit the shape of the hatched area to the circular Gaussian surface in order to maximize the volume above it.

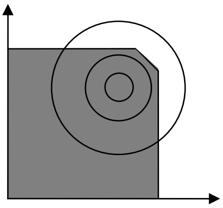

Fig. 13. Demonstration of approximating the Gaussian surface's projection onto the plane of the two axes

We considered a simple triangle model with three routers. But in a tree-topology domain we have several triangles above each other. In this case the normal distribution has the advantage that the sum of two random variables of normal distribution remains normal, expectation value and variance is added. When simply adding random variables in our model, we assume no packet loss and neglect the delay along the alternative link.

The optimal value for m exists probably for all not pathologically chosen distributions, because when m is small enough, the hatched area with a slight increment of m will be much greater than the lost triangle, as can be seen in *Fig. 4*. So the packet loss probability will decrease when m starts to increase, and after an interval it must increase, because the total ingoing capacity of router #0 will decrease. Thus, there must be an optimal value for m, but as we have seen it is difficult to obtain a closed form solution in many cases. As this method should be applied in network planning phase the fast and precise computation is not necessary, but simple approximations can provide a rule of thumb.

5. Simulation

To validate our method, we analysed the performance of these protocols using the OMNET++ simulation environment. To examine this method we have implemented a simulation model in OMNeT++ [13], which is a discrete event simulation system. A network model in OMNeT++ consists of hierarchically nested modules. Through their connections modules are able to pass messages to each other. The topology of modules is described in NED (NEtwork Description Language); operation of modules is to be implemented in C++.

We designed and implemented an IP mobility simulator in this simulation environment and investigated our new method. It supports both macro- and micro-mobility. We created a sample network that contains a correspondent host, several mobile hosts and two micro-mobility domains operating according to the assumptions in Section 3.2. Our two test domains consist of a gateway router that is responsible to handle the communication towards the Internet and also acts as a home agent, five additional routers and six base stations (radio access points). These devices represent a micro-mobility domain; they are encapsulated in an OMNeT++ compound module. The architecture of our test domain can be seen in *Fig. 14*, which was taken from OMNeT++ Tcl/Tk graphical user interface. The micro-mobility domains are contained by a module called AS, which can be used later for modelling a provider's network or AAA (Authentication, Authorization and Accounting) domains. Currently they are only a level in the IP addressing hierarchy. Inside this domain there can be also a wired host beside the micro-mobility domains.

These AS-es are interconnected via a backbone network, which routes packets based on their IP address prefix that identifies the destination AS. An AS can exist without any wireless access part. At the border of an AS there is a router that routes packets based on the second address prefix. We use a separate AS for a correspondent host being far away from the mobile hosts. Between the mobiles and base stations we use an Air object modelling the radio channel and handling the movement of mobiles.

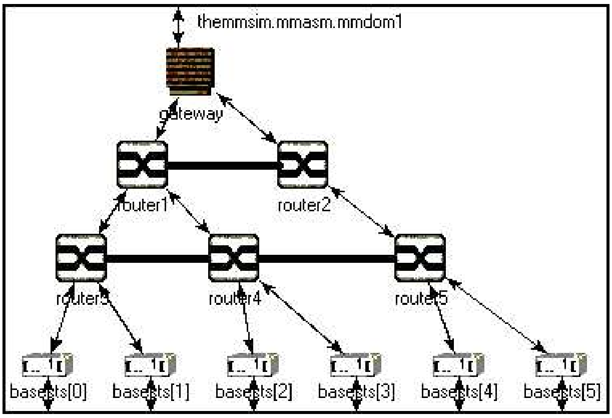

Fig. 14. The architecture of the test domain. Alternative links are the thick solid horizontal lines

We have a tree of routers with three levels; the additional alternative links are denoted by thick horizontal solid lines. We have six base stations, total 12. They are placed in a hexagonal manner in 3 rows and 4 columns as can be seen in *Fig. 15*. The hierarchy of the above mentions modules can be summarized as (at the top level they are within a network module called mmsim):

- Backbone (contains a router (uses first address prefix),
- AS1 (with a router and a correspondent node),
- AS2,
  - Router (uses second address prefix),
  - Correspondent node,
  - Two domains, in each of them: 1 gateway, 5 routers and 6 base stations,
- Air,
- Mobiles.

The users can move according to the random walk mobility model [6] and independently from one another inside the simulation area. Mobiles have a destination location and a speed value pointing towards that destination. They take a step in each time slot, its length can be configures. If they reach their destinations, they choose other ones with certain speed values, and continue their ways. This method ensures that mobiles will not leave the simulation area. Or alternatively the reference point model [6] can be used where mobiles move according to the random walk model, but they must stay around a reference point. This reference point itself moves according to the random walk model. Except this, mobiles move independently from each other. This model is suitable for modelling users that overload a certain part of the network. If we choose the borders around the reference point,

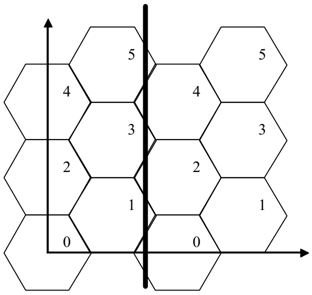

Fig. 15. The placement of base stations. Border of domains is along the thick vertical solid line

within which mobiles are allowed to move, small enough compared to the whole domain's area, mobiles will obviously load only a part of the domain. The base stations did not cover the whole area, so mobiles may also lose their connections to the network. At the beginning of the simulation, users are homogeneously distributed over this area. Every user moves from a random position to another randomly chosen position. The traffic of the hosts is modelled as a random ON-OFF source [11]. If the mobile is ON it generates IP packets with exponential inter-packet time addressed to the correspondent host, which can be wired or mobile. The length of ON and OFF intervals is also modelled as an exponential random variable. The mobiles send packets of 200 bytes length, the link capacity in the domain is 500. The length of registration messages is 40 bytes.

The main reason of packet loss is the congestion at routers in the micro-mobility domains. We set the Mobile IP's binding cache, and micro-mobility protocol's soft-state cache timeout (and also their capacity) to a relatively great value, and mobiles had to refresh them relatively rarely. So the probability of the event that the home agent or a router has no entry (or no size for a new entry) for the given mobile host was small. When no valid entry was found in a router or home agent, it would have to drop the packet because it does not know any route to the destination. The capacities in the backbone network and in the correspondent node's network were also chosen appropriately. After that we assumed that the packets are lost because of congestion in routers of domains. We changed the traffic load from mobile hosts by increasing their number. According to the link capacities mentioned above we did not need too much mobiles, they can induce congestion easily.

5.1. Simulation Results

In the first diagram we show the number of lost packets (as percentage of total number of packets) in the function of the mobile hosts' number. The values of the load cover a range; within which there is an overloaded case and also a nearly empty network (*Fig. 16*). We can say that using alternative paths when there is congestion in the network we can improve the performance of the micro-mobility domain from the viewpoint of packet loss. The dashed lines represent the case without alternative links, the solid lines with them. The difference (between the dashed-solid curve pairs with the same marks, i.e. triangles or squares) is more significant in an overloaded network (at higher number of mobile hosts), here the ratio is much better. By a low load the difference is not so significant, but there is reasonable because in that case the packet loss is less probable so it is nothing to improve. In that case there is no need for alternative paths with these router capacities. But it means that if we have such few users we can decrease the capacities of routers – we can apply smaller domain routers if possible. The difference between the two mobility models can also be seen in *Fig. 16*. The curve marked by small triangles shows the results with the basic random walk model, the square marking denotes the random waypoint mobility model. As was expected in the case of the random waypoint mobility model the performance of the network is less than with the basic random walk model. The reason is that in this case the traffic loads only certain parts of the domain around the reference point of the movement model. Alternative link enhances the performance with both models.

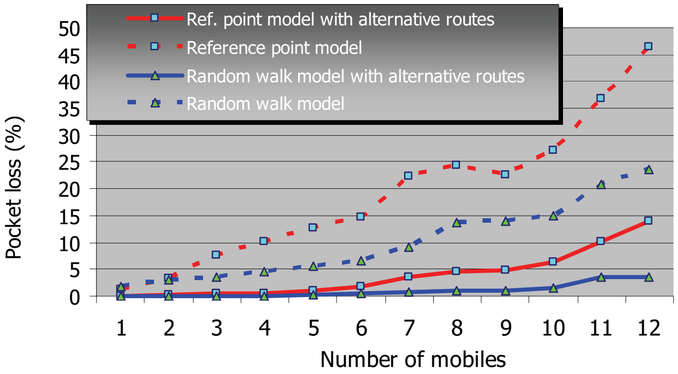

Fig. 16. Effect of network load on packet loss

We investigated the effect of the mobiles' speed on the packet loss. The results can be seen in *Fig. 17*. The speed values of the x-axis represent maximum values. Mobiles can choose their speeds from the interval of [0, max. speed]. The number of mobiles was chosen as 5 based on the previous graph. The line types and marking are the same as in the previous figure. The relative placement of curves remains the same, so applying the basic random walk model results in smaller packet loss than the random waypoint mobility model; and alternative routes can decrease the packet loss.

In simulations we also investigated separately the traffic upwards and downwards. There was no important difference between the two directions, because the traffic load from the correspondent hosts and from mobile hosts has the same properties in the simulation and the algorithm handles these two cases in the same manner – uses alternative paths.

From the results we could not obtain any dependence, the fluctuations are caused by the randomness in the simulation. Empirically it can be interpreted as the load is independent from host mobility; the important factor is how close the demands are to each other, rather than their speed. We also began to examine how we should split a given total capacity in the whole domain. The packet loss could be decreased by decreasing capacity downwards in the domain – as can be expected from theoretical considerations, but we are still working on this task.

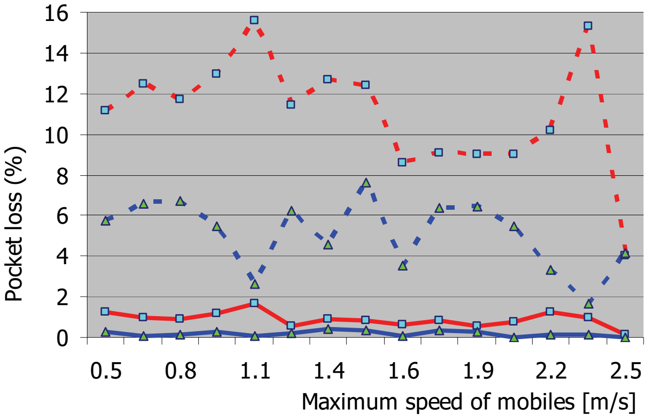

Fig. 17. The effect of mobiles' speed on packet loss

6. Conclusion

In this paper we presented a new method for improving the performance of tree-based IP micro-mobility proposals. We surveyed the micro-mobility proposals, introduced our micro-mobility domain model and added further links to the tree topology. This solution is expected to decrease packet loss, increase the usage of the domain and provide a possible solution for the problem of tree-nodes being single points of failures.

We introduced our theoretical calculations in which we were able to calculate the optimal crosslink capacity within a triangle if the total capacity and the traffic's distribution were given. Our simulation results were also presented. We could decrease the probability of packet loss in the micro-mobility domain. The results showed that the mobiles' speeds do not have any strong influence on the packet loss. Investigating separately traffic upwards and downwards did not provided any reasonable difference assuming similar traffic models in correspondent and mobile nodes.

In the future we plan to improve our simulation, implement more traffic and mobility models, extending them with further micro-mobility protocols, especially Hierarchical Mobile IPv6. As we mentioned earlier this traffic model needs much improvement to model the real traffic conditions more accurately than the currently applied one. The characteristics of the traffic must depend on the type of the traffic we simulate. E.g. a real-time connection generates a different kind of traffic than a voice call or the file downloading. The random walk movement modelling must also be refined. Our analytical model also needs improvement, because no user movements are considered. Usually ongoing calls are more important to keep alive than allow new connections. This should be considered in our model.

References

[1] BLAKE, S. et al., *An Architecture for Differentiated Services*, IETF RFC-2475, 1998.

[2] CHASKAR, H. – KOODLI, R., QoS Support in Mobile IP version 6, *IEEE Broadband Wireless Summit (Networld+Interop)*, May 2001.

[3] DAS, S. – MISRA, A. – AGRAWAL, P., TeleMIP: Telecommunications-Enhanced Mobile IP Architecture for Fast Intradomain Mobility, *IEEE Personal Communications*, **7** (4) August 2000, pp. 50–58.

[4] DEERING, S. – HINDEN, R., *Internet Protocol, Version 6 (IPv6) Specification*, RFC-2460, Dec. 1998] and its extensions.

[5] GLOSS, B. – HAUSER, C., The IP Micro Mobility Approach, *Proc of EUNICE 2000 Open European Summer School on Innovative Internet Applications*, Enschede, 2000, pp. 195–202.

[6] HONG, X. – GERLA, M. – PEI, G. – CHIANG, C., A Group Mobility Model for ad hoc Wireless Networks, In Proceedings of the *ACM International Workshop on Modelling and Simulations of Wireless and Mobile Systems* (MSWiM'99), August 1999.

[7] JOHNSON, D. – PERKINS, C. – ARKKO, J., *Mobility support in IPv6*, IETF RFC-3775, June 2004.

[8] KEMPF, J., *Dormant Mode Host Alerting ('IP Paging') Problem Statement*, IETF RFC 3132, June 2001.

[9] KESZEI, CS. – MANNER, J. – TURÁNYI, Z. R. – VALKÓ, A. G., Mobility Management and QoS in BRAIN Access Networks, *BRAIN Workshop*, London, January 2000.

[10] KOODLI, R., *Fast Handovers for Mobile IPv6*, IETF Internet draft, July 2004.

[11] LAM, D. – COX, C. D. – WIDOM, J., Teletraffic Modelling for Personal Communications Services, *IEEE Communications Magazine*, February 1997.

[12] MALINEN, J. T. – LE, F. – PERKINS, C. E., *Mobile IPv6 Regional Registrations*, IETF draft, March 2001.

[13] OMNeT++ Home Page, http://www.omnetpp.org/.

[14] PATIL, B., IP Mobility Ensures Seamless Roaming, *Communication systems design*, Feb. 2003. http://www.commsdesign.com/csdmag/sections/cover{_}story/showArticle.jhtml?articleID=16500515

[15] PERKINS, C. ed.: *IP Mobility Support for IPv4*, IETF RFC-3344, August 2002.

[16] RAMJEE, R. et al., HAWAII: A Domain-based Approach for Supporting Mobility in Wide-area Wireless Networks, *7th International Conf. on Network Protocols*, Toronto, Canada, Oct. 31–Nov 3. 1999. p. 283.

[17] SOLIMAN, H. – CASTELLUCCIA, C. – MALKI, K. E. – BELLIER L., *Hierarchical Mobile IPv6 mobility management*, IETF Internet draft, June 2004.

[18] Third Generation Partnership Project Home Page, http://www.3gpp.org, http://www.3gpp2.org

[19] VALKÓ, A., Cellular IP – A New Approach to Internet Host Mobility, *ACM Computer Communication Review*, **29** (1), January 1999, pp. 50–65.