Paper

Interworking and Cross-layer Service Discovery Extensions for IEEE 802.11s Wireless Mesh Standard

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Abstract—With the rapid popularization of mobile end-user electronic devices, wireless network technologies begin to play a crucial role as networks access technologies. While classic point-to-multipoint wireless access systems, based on fixed infrastructure of base stations providing access to clients, remain the main most popular solution, an increasing attention is devoted to wireless mesh systems, where each connecting client can extend overall resources of the network by becoming a network node capable of forwarding transit traffic. This ability results in severe reduction of the necessary network infrastructure, provides through coverage (thereby offering significant step towards ubiquity of network access) and offers massive redundancy. One of the most promising wireless mesh solutions currently being developed is an IEEE 802.11s standard, based on popular Wi-Fi technology. It combines low deployment costs with comprehensive suite of mechanisms able to operate a self-forming, autoconfigurable, dynamically extending, and secure mesh solution. However, despite its advantages, the standard lacks sufficient support for a number of functionalities, which can lead to significant inefficiency and degradation of service quality in real-world IEEE 802.11s network deployments. In the paper we propose a number of extensions of IEEE 802.11s mechanisms, designed to provide better service quality in case of real-world deployment scenarios, especially in case of large systems. Both propositions introduce modifications to mesh path discovery and interworking procedures, while retaining compatibility with standard solution. Their basic functionality and efficiency have been verified by means of simulation model in large-scale, self-organizing mesh structure. Subsequently they have been implemented and tested in real-world, access network testbed deployment. The results clearly indicate their utility, particularly in case of larger deployments of this network system type.

Keywords—802.11, cross-layer, interworking, mesh, wireless networks.

1. Introduction

The rapid growth of the quantity and capabilities of end-user electronic devices, both stationary and mobile, resulted in their use in increasing number of applications. Their popularity and high functionality created such concepts as:

– **Smart Cities**, emphasizing ubiquity of ICT-based (Information and Communication Technology) services in as many elements of our daily lives as possible,

– **Internet of Things**, proposing an introduction of electronic devices into as many elements of our physical environment as possible,

– **Cloud Computing**, bringing ability to use computing resources, both hardware and software, as services provided by ubiquitous infrastructure,

– **Machine-to-Machine** systems, allowing free interaction of different devices to extend their functionality set and overall usefulness.

It is evident from the above list of examples, that number of electronic devices will continue to grow and that an efficient communication between them is a crucial component of modern ICT systems. Requirements set before both core and access network systems are high and will continue to grow, both in terms of raw throughput and quality of service (QoS) provided. Apart from these requirements, growing percentage of mobile devices and associated services creates new requirement of ubiquitous network access - user should always be offered some form of network connectivity, as its lack would result a severe reduction of device's functionality. Modern smartphone operating systems and various "aaS" (as a Service) approaches are good examples of this trend. Wireless network technologies have a crucial role in access networks of such systems, as cable-based solutions are of limited utility in case of necessity to provide network access to easily portable or mobile devices. Moreover, their use is often preferable even in case of stationary devices, due to lack of necessity of deploying a costly and cumbersome cable infrastructure. Most of popular wireless access systems follow point-to-multipoint architecture, with operator maintained infrastructure of access points or base stations (connected with fast cable or point-to-point wireless links), each serving a set of client devices over its coverage area. Such systems must be carefully designed, taking into account both current and future signal propagation characteristics, expected user density, traffic requirements and economic constraints.

However, a new emerging type of wireless network can be used to create system, where each connecting client can extend its overall resources by becoming a network node capable of forwarding transit traffic. Such ability allows a severe reduction of the necessary operator provided infrastructure, compared to classic point-to-multipoint systems. It is also a significant step towards ubiquity of network access, as mesh systems tend to provide through coverage. Mesh networks can be used in a variety of applications, starting from small ad hoc systems, through a highly robust and redundant infrastructure of an access network, and ending with emergency or military communication networks or self-organizing office/building/campus integrated infrastructure systems. In all of these scenarios, the main advantages of mesh networks include autoconfiguration and self-forming abilities. However, as an emerging technology, fully self-forming mesh solutions are still in process of being standardized and a number of technical problems remain to be solved.

2. IEEE 802.11s Standard

One of the most promising mesh solutions currently being developed is an IEEE 802.11s standard [1], aimed to create a broadband, fully autoconfigurable, dynamically extending, and secure mesh solution, based on widely popular Wi-Fi (IEEE 802.11 [2]) wireless local area network (WLAN) technology. It is designed to serve in wide variety of environments, starting with small ad-hoc, isolated networks (for example, groups of laptops), through industrial network deployments, office LANs, and ending with large, self-extending, public access systems. The created mesh structure is called a Mesh Basic Service Set (MBSS). The fact that this solution is based on cheap and popular Wi-Fi technology and can be deployed on existing hardware makes it one of very few mesh solutions able to successfully appear and remain on popular WLAN market. Additionally, a number of design decision have been made to make an IEEE 802.11s mesh as compatible and as easy as possible to integrate with existing network systems. Examples include mesh gates – specialized network nodes responsible for integration with external networks, hybrid routing protocol – ensuring that there are relatively small delays in routing to external destinations, higher layer transparency – making mesh network seem as a single Ethernet broadcast domain, complete with 802.1D [3] compatibility (bridging and spanning tree protocol). It is evident, that standard authors aimed to provide a robust building block for modern networks systems, both functional and inexpensive to deploy.

Due to its robustness, an IEEE 802.11s-based mesh can be used in a variety of previously described roles, including the most complex office/building/campus infrastructure system. Despite the above advantages, a number of areas in the discussed standard lack sufficient support, which can lead to significant inefficiency and degradation of service quality in real-world IEEE 802.11s network deployments.

The first serious limitation is the fact, that the standard in its current form does not include support for creating multichannel mesh networks, which leads to severe throughput degradation due to both intra and inter-path interference. This limitation is especially important in case of dense mesh networks, where each transit node directly affects a high number of neighboring nodes. The inability to perform concurrent transmissions within a given neighborhood by spreading them across a number of orthogonal frequency channels or for a single node to concurrently receive and transmit on different channels results in highly inefficient RF resource utilization. In this situation, each additional hop on the transmission path consumes high amount of limited RF resources, not only resulting in lowering QoS parameters of a given transmission, due to intra-path interference, but also affecting all neighboring transmission paths, causing inter-path interference. Figure 1 illustrates the theoretical maximum throughput as a function of number of hops in a single channel Wi-Fi mesh, where only one transmission is currently conducted (there is no inter-path interference). Two cases have been considered:

– an optimistic – where it is assumed, that each of transit nodes has only two neighbors in interference range, its predecessor and the next node on transmission path,
– a pessimistic – where it is assumed that all nodes are within interference range of each other.

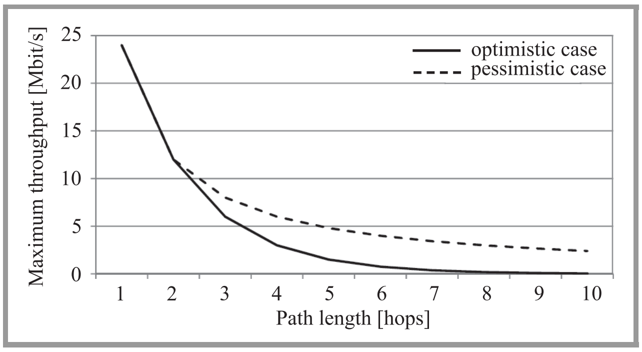

Fig. 1. Maximum theoretical single-channel mesh throughput for IEEE 802.11g transmission technology.

As can be seen from the above description of efficiency problems of RF resource usage in case of single channel mesh networks, it is crucial to limit mesh transmission path length (number of hops) as much as possible – it will result in both resource conservation, better (and more predictable) QoS level for users.

This task requires appropriate path discovery protocols, which are adequately addressed in the current standard by employing a hybrid (reactive/proactive) solution. However, we would like to propose an extension of these standard mechanisms, which can provide significant advantages in case of larger mesh structures.

3. IEEE 802.11s Path Selection Mechanism

The discussed standard utilizes Mesh Discovery and Mesh Peering Management protocols to discover neighbor nodes and create peer relationship between them, creating the base topology of a mesh system. Its operation procedures are outside of our current interest, as for the purpose of this research, we assume an already existing system topology.

To discover transmission paths over a given network topology, the IEEE802.11s system utilizes Hybrid Wireless Mesh Protocol (HWMP). This hybrid protocol, consisting of both reactive and proactive path discovery mechanisms, is able to function concurrently to provide both fast response, adherence to changing transmission conditions, and minimization of management overhead.

Moreover, the standard allows for extensibility of path selection protocols, including the ability to use alternate path discovery solutions, as long as the same, single solution is utilized uniformly through the mesh network. Despite the fact, the obligatory HWMP protocol must also be supported by all IEEE 802.11s devices, for the sake of compatibility. Peering management mechanisms are responsible for assessing node capabilities and deciding, if connecting station is able to participate in a given mesh procedures. The same mechanisms are then responsible for configuration of the newly connected node to use the appropriate path selection protocol.

The basic path discovery mechanism of HWMP is a reactive Radio Metric Ad hoc On-Demand Distance Vector (RM-AODV) protocol. It is a modification of well-known AODV protocol [4], but extended to use a radio aware link routing metric. In case of unmodified AODV metric used for path selection is a number of transmission hops on a given path. Such solution does not take into account the quality of links traversed which makes it poorly suited for wireless environment, where different links can provide a radically different transmission quality. To address these issues, RM-AODV employs Airtime Metric as a measure of link quality, taking into account both their current maximum data rate and transmission error rate – see Eq. (1)

$$c_a = \left[O + \frac{B_t}{r} \right] \frac{1}{1 - e_f}, \tag{1}$$

where c_a is link Airtime Metric value, O – technology dependent transmission overhead, r – link throughput, B_t – size of the test frame and e_f – frame error rate for a given B_t.

Link load is not taken into account directly, due to rapid and unpredictable changes of this parameter in case of wireless multihop systems, but its impact is reflected by link error rate parameter, which is significantly higher in case of highly loaded links. Airtime Metric can be seen as an amount of link resources necessary to transmit a frame.

3.1. Reactive Routing

As a reactive protocol, RM-AODV is activated by a source station, when it has a frame to send to a previously unknown destination, or destination for which forwarding information is suspected not to be current. In such case the node initiates path discovery. Each new path discovery initiated by a given station is assigned a unique (incrementing) HWMP Sequence Number. This number, along with intended destination address and path metric field set to 0 is included in Path Request (PREQ) message, subsequently sent by originating station to all of its neighbors as a broadcast HWMP Path Selection frame. Each receiving neighbor checks if it already received PREQ with:

- greater HWMP Sequence Number – the PREQ is considered to contain stale information and is discarded, as more recent PREQ already have been received,
- the same HWMP Sequence Number and the same or greater path metric – the PREQ contains current information, but it is also discarded, because the node already received PREQ of the same discovery which arrived through the better path (smaller path metric),
- the same HWMP Sequence Number and smaller path metric – the PREQ contains current information and arrived by the best path (smallest metric) yet.

In the last case the receiving station updates its forwarding information, by remembering the station that it received PREP from, as its best next-hop on a path to PREQ originator. The station then increases path metric of received PREP by the metric of the link it arrived by, and re-broadcasts it to its neighbors. That way all stations in the mesh learn a next-hop towards PREQ originator, thereby creating mesh paths toward it. It should be noted, that the described procedure is conducted with use of HWMP Path Selection Frames sent to a broadcast address and such frames are not subject to reception acknowledgement and retransmission procedures. Such solution have been chosen to lower the resource consumption and process delay at a cost possibility of missing an optimal path due to a loss of Path Selection frames.

When an intended recipient of the communication (destination station) receives PREQ which would trigger a re-broadcast according to above rules, it updates its forwarding information and, instead of re-broadcasting PREQ sends a unicast Path Replay (PREP) to PREQ originator along the just discovered (reverse) path. The PREP is forwarded by transit nodes along the path, each of them updating its forwarding information by remembering from which neighbor it received PREP, thus forming path to PREP originator. As PREP reaches the source station, a bidirectional path between the initiator of the discovery procedure and its subject is formed, by presence of current next-hop forwarding information in all transit nodes.

It should be noted, that it is possible that the transit stations will re-broadcast PREP from the same discovery procedure multiple times and the destination node will generate multiple PREP messages, if they receive multiple subsequent PREQs with decreasing path metric. However, due to the fact that smaller metric most often corresponds to shorter transmission delay, it is not likely.

It is evident that such procedure can be time consuming, especially in case of large mesh networks and distant destinations. Moreover, broadcast procedures tend to consume a considerable amount of resources. To optimize the described procedure, it is possible to allow transit stations which already have current next-hop information toward the destination station, to respond with PREP. That allows the source station to learn the forward path to destination quickly, but its PREQ still must be broadcasted all the way towards the destination station, to form the reverse path from destination to source.

3.2. Proactive Routing

Apart from the obligatory RM-AODV protocol, the IEEE 802.11s standard defines an optional proactive path discovery solution, which can be deployed concurrently with RM-AODV. This solution, sometimes called Tree-Based Routing (TBR) protocol, consists of two independent mechanisms: Proactive Path Request (PPREQ) and Root Announcement (RANN). Both can be used to proactively create and maintain current paths between a selected mesh station (Root Mesh Station) and all other stations in the mesh. Moreover, they reuse a significant number of mechanisms of RM-AODV protocol, thereby simplifying their implementation.

In case of the first approach, PPREQ, a selected root station periodically originates PPREQ messages, which can be thought of as PREQ messages addressed to a broadcast destination. They are re-broadcasted through the network according to the same rules as in case of RM-AODV. That results in periodic refresh of unidirectional paths leading towards Root Station in all stations of the mesh. If mesh station predicts that a bidirectional path will be required, it can respond to PPREQ with unicast PPREP, which will be forwarded to Root Station and create the path in opposite direction. Root Station can also request that all stations respond in such fashion.

Due to a relatively high consumption of resources in case of PPREQ method, an alternative solution has been included in the standard – the Root Announcement mechanism (RANN). Instead of periodically sending PPREQ messages in HWMP Path Selection frames, Root Station can choose to send RANN messages instead. The first difference between those two messages is that RANN does not need to be send in a dedicated frame, but can be included in beacon frames, which are periodically broadcasted by each mesh station as a part of neighbor discovery mechanism, resulting in significant resource conservation.

Moreover, while RANN messages are propagated through the network using the same procedure as PPREQ messages, their reception does not result in updating of receiving station forwarding information. Instead they can be used to decide, if active update of this information should be undertaken. For this purpose the information from which neighbor RANN message has been received is stored, and its path metric is compared with metric of the current path that the station has to a Root Station. If the station does not have a path to Root Station or if its metric is worse than RANN metric, the station can perform a reactive, unicast, RANN assisted path discovery.

For that purpose, the station sends a unicast PREQ message to the Root, by forwarding it to the station form which it received RANN announcement. Such PREQ is ten forwarded retracing RANN path to Root Station, updating forwarding information in transit stations and forming path towards PREQ originator. Upon reception of the PREQ, Root Station responds with unicast PREP, which forms the path in opposite direction.

Due to strictly unicast nature of such discovery, it is both efficient (no broadcast flooding) and reliable, as unicast frames are subject to reception acknowledgement and retransmission.

3.3. Interworking

As stated before, IEEE 802.11s standard aims to provide easy integration of mesh network with other network technologies, in particular Ethernet wired technologies. An IEEE 802.11s MBSS integrates with external networks as another IEEE 802 access domain, complete with support for various IEEE 802.1D mechanisms (such as bridging). However, in contrast to other popular IEEE 802 technologies (for example Ethernet), the MBSS operation is not primarily based on broadcast data delivery, as such approach is not acceptable due to limited resources of wireless system.

In this situation, delivery of data to addresses unknown within MBSS cannot be conducted by simple broadcasting it to all stations for the bridging ones to receive and forward to external systems. To emulate this popular method of delivery, mesh stations connected to external networks, named Mesh Gates, support an extended suite of mesh mechanisms.

Presence of Mesh Gates is advertised in the MBSS by proactive PPREQ/PPREP messages with a special Gate Announcement field set (if Mesh Gate is also Root Station) or dedicated Gate Announcement frames (GANN), distributed in fashion similar to already described RANN messages.

Each Mesh Gate maintains a dedicated database (Proxy Information) of addresses known to be located in external networks accessible through a given gate. Moreover it forwards its contents to other Mesh Gates through MBSS with use of Proxy Update (PXU) messages. That makes all Mesh Gates aware, which gate should receive frames addressed to a particular external destination. If any other Mesh Gate receives frame proxied by other Mesh Gate, it will forward it to the correct gate through MBSS. However it should be noted, that both proxy information exchange and gate to gate data forwarding is conducted through MBSS and thus consuming limited RF resources.

Due to the fact that Mesh Gate is functional equivalent of IEEE 802.1D bridge, if more than one gate is connected to a given external network, only one of them can be active at a time, as more could lead to creation of broadcast loops. For this purpose a dedicated protocol must be employed at Mesh Gates – most often a well-known Rapid Spanning Tree Protocol (RSTP) [3].

Mesh station which cannot discover a MBSS path to a given address, assumes that it is located in external network. In such case it sends the data frame to all known Mesh Gates, for further delivery – due to RSTP activity, the frame is delivered to each external network only once, as only one

Mesh Gate is active per such network. To optimize further data delivery, Mesh Gate appropriate for a given destination sends PXU message to the station, which allows it to use a single Mesh Gate in continued transmission.

4. Path Discovery and Interworking Extensions

The described mechanisms allow for a significant flexibility in path discovery operations, taking advantage of both reactive routing optimized paths created on demand, and fast connection establishment to critical mesh locations, provided by proactive solutions. Moreover, interworking with outside networks is a subject of much attention, allowing seamless integration of mesh network with other IEEE 802 layer 2 ISO-OSI systems.

However, while IEEE 802.11s mesh network can provide connectivity with destinations in external networks, it is unable to use resources provided by these networks to support connectivity of intra-mesh destinations. Furthermore, it is unable to utilize multiple mesh gates connecting MBSS with the same external network segment (RSTP protocol disables frame forwarding in all but one) resulting in formation of longer paths within the MBSS, as Mesh Gates near a given station can be disabled by RSTP.

The proposed modifications of IEEE 802.11s mesh path discovery and forwarding protocols can be summarized as follows:

– introduction of ability to form a peering relationship between mesh gates, using external network as transmission medium,

– introduction of ability for a mesh station to use any of the mesh gates connected to a single, external network segment.

The first proposition allows using fast, cable connections frequently present between mesh gates connected to fixed infrastructure, to form transmission paths between intra-MBSS destinations. Due to the fact that Airtime Link Metric for such transmission link will be very low (throughput higher and error rate lower than in wireless technology by several order of magnitude), use of such links will be highly preferred.

Also, because it is highly probable in large mesh deployment, that there is a significant number of mesh gates able to communicate with use of external network and distributed through the mesh in more or less uniform fashion, there is a high probability of reducing the average path lengths of intra-mesh transmission. In fact, for a standard mesh deployment in large, multi-company office building, utilizing about 0.5–1 mesh gate for a single floor, the described mechanism will trend to reduce average mesh path lengths to 2–3 hops – which makes it suitable even for real-time multimedia communication.

To provide such functionality it is necessary to allow transmission of frames of IEEE 802.11s format through the external network. For the sake of simplicity and robustness (ability to function in case of different external network technologies) of the proposed solution and maintaining compatibility with IEEE 802.11s standard, to employ a simple mesh frame encapsulation in external network's unicast frames for the purpose is proposed.

Moreover, it is necessary to provide the ability for mesh gates to detect each other presence and addresses for unicast communication through the external network. In case of popular broadcast networks, such as Ethernet, an encapsulation of standard mesh peering messages and their transmission to broadcast address will serve the purpose. However we should remember that in case of wireless network, peer relation establishment and maintenance mechanisms use constantly and frequently generated messages, which are not retransmitted by receiving nodes, thereby limiting such traffic to 1-hop neighborhood. In case of broadcast transmission in wired network, such messages will be transmitted across the whole broadcast domain, consuming network resources. While dissemination of mesh gate presence information widely through the network is advantageous to our purpose, the frequency required in case of unstable IEEE 802.11 RF environment is highly superfluous in case of cable technologies. Because of that, frequency of mesh detection and peering message exchanges through the cable network need to be reduced. Moreover, a multicast group transmission can be considered instead of broadcast, if used external network technology supports it.

As an additional advantage of the described modification, mesh gate to mesh gate communication, such as proxy related management messages and gate-to-gate data forwarding, can be accomplished by forwarding appropriate messages through the external network instead of MBSS, thereby conserving network resources in general, and particularly in important Mesh Gate neighborhoods, where we expect a high levels of network traffic.

Also to allow using all existing mesh gates as points of contact with external networks is proposed, in contrast with unmodified IEEE 802.11s standard, where only one active mesh gate can be connected to the same external network segment due to already mentioned broadcast loops effect.

The proposal limits using of RSTP to disabling forwarding between Mesh Gate and external network, while leaving remaining functionality of Mesh Gate active. The frames addressed to external (or unknown) addresses, received by non-forwarding Mesh Gates will be delivered (by the mesh link through external network, due to is low Airtime Metric), to fully active gate for further forwarding. This modification will prevent the unnecessary reduction of the number of Mesh Gates which can be used by mesh station to reach external networks, thereby limiting path lengths through MBSS.

However, that station initially forwards frames with unknown address to all known Mesh Gates. Due to our modification it would result in unnecessary traffic and forwarding of multiple copies of such frames to a single external network. To prevent it, an additional element of Gate Announcement messages is introduced, which uniquely identifies the network segment a sending mesh gate is connected to (Segment Identifier – SGID), by containing the address of Mesh Gate currently actively forwarding to this segment. Mesh stations will send data frames only to one Mesh Gate from a group of Mesh Gates sharing the same SGID.

To illustrate the results of introduction of the proposed extensions, a simulation experiment utilizing OMNet++ simulation engine [5] was performed. As modifications are intended mainly for larger mesh networks, a series of simulations of systems containing 100 stations deployed randomly over 2000×2000 m area were performed. A log-distance path loss propagation model has been used [6], to predict the loss a signal encounters in densely populated areas. All nodes were equipped with a single IEEE 802.11g [7] radio interface using the same RF transmission channel.

The standard IEEE 802.11s discovery and peering mechanisms were then used to form a mesh structure, but configured to not form peer links with nodes of medium or worse link quality, if the node if able to form at least one better quality peer link. It limited the number of links in the mesh structure, but improved their quality.

For each scenario a 50 simulation runs have been performed, each with 1 test TCP connection between randomly selected mesh stations at least 500 m apart, and 20 such connections generating background traffic. A chosen number of modified Mesh Gates have been activated at randomly selected stations, starting with 0 (unmodified IEEE 802.11s MBSS). All Mesh Gates are connected with a single Gigabit Ethernet network.

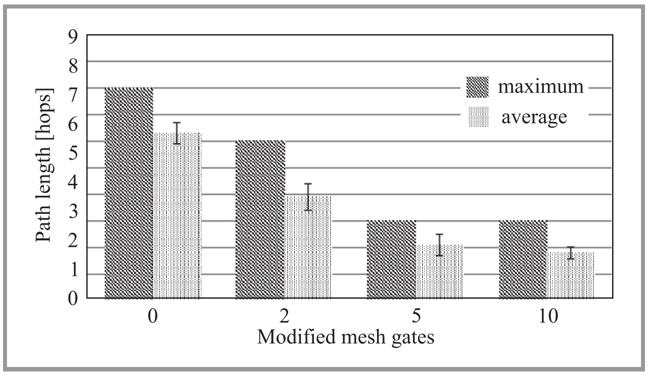

Fig. 2. Maximum and average wireless path length for different number of modified Mesh Gates.

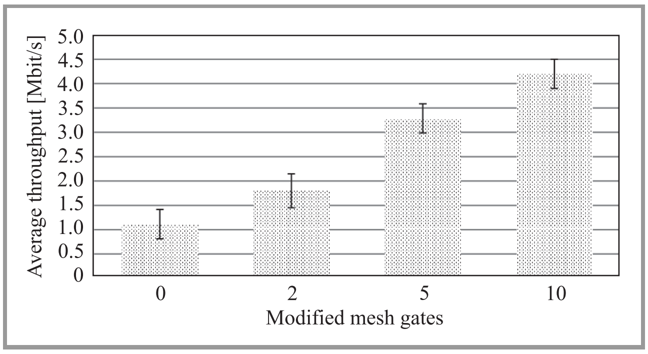

Fig. 3. Average test connection throughput for different number of modified Mesh Gates.

The results, in form of maximum and average MBSS wireless path length and average throughput for test connection, are presented in Figs. 2 and 3.

It is evident, that presence of Mesh Gates modified in proposed fashion results in reduction of both average and maximum wireless path lengths. Moreover, obtained throughput of the connection is also significantly better, despite the observed tendency to concentrate transmission paths in vicinity of Mesh Gates. Resulting concentration of traffic does not impact the transmission as bad as intra-path interference in case of longer mesh paths.

5. Cross-layer Application Discovery Extension

On the other hand, the fact that traffic sources, such as various application layer servers, can be located within a mesh network (one of its most attractive usage scenarios is self-organizing LAN/campus infrastructure), makes it important to utilize efficient application level service discovery solutions. Such mechanisms will allow clients to connect to the most appropriate server in terms of quality of service and resource consumption. Unfortunately, the fact that an IEEE 801.11s mesh is presented to higher ISO-OSI layers as a single layer 2 broadcast domain, does not allow any higher layer mechanisms to obtain reliable information about its structure. For example, IP-based service discovery procedures can be used to select a server, from a preconfigured client-side list, which provides client with the best IP connectivity at a given moment. They are not, however, taking into account an actual mesh transmission path length – for IP layer all destinations within a mesh are only 1 hop away. Such approach can lead to inefficiently long transmission paths, and dynamic organization of mesh network tends to make such paths very unstable. The analysis based on real-world device usage data in multi-office building environment confirm the above problem and indicates high QoS parameter variation for long mesh paths.

To mitigate this problem a cross-layer integration solution, allowing application level services and servers to advertise themselves using layer 2 mesh management messages is proposed. Such approach allows a mesh structure aware dissemination of information about available services and facilitates a selection of the most appropriate server for a given client. Additionally, application servers can include elements such as:

- information about supported access methods, authentication schemes and other client requirements,
- server load information,
- an initial configuration information for connecting clients,

in advertisement messages, resulting in significant reduction of initial high level service access time.

For the servers to advertise their presence, creaton a new type of IEEE 802.11s management message – Higher Layer Service Advertisement (HLSA) is proposed. This message is to be generated by active application servers in form based on RANN message. All the information present in RANN message should be included in HLSA, functionally making the generating server a Root Station using Root Announcement proactive mechanism. Furthermore, the server should include in the message additional informational elements, describing the provided application layer service. A specific set of information parameters will vary depending on a particular service type, but the information should be prepared in a way to minimize high layer message exchanges necessary to access the service. It is also advisable for the servers to set Time To Live (TTL) field in HLSA messages in accordance with their requirements of the service they provide – that way the dissemination of HLSA messages is limited to clients which are able to access the service with satisfying Quality of Experience, and network resources are conserved.
Stations receiving HLSA should process it in the same way as RANN messages, by dispersing it through the network, up to TTL limit. That way all of receiving clients will obtain information about:

– services available in the network,

– Airtime Metric and number of hops to the most appropriate server for a given client,

– expected server performance (for example a measure of current server load) and a set of application level, service specific requirements for the client, allowing it to decide if it should use a given server for service access,

– an optional set of network layer (for example IP-MAC address mapping making broadcast ARP resolution unnecessary) and service specific configuration parameters.

As a result a number of valuable advantages can be expected:

– a significant reduction of initial service access delay for connecting clients,

– easy selection of the nearest available servers resulting in shorter transmission paths, providing both good and stable transmission parameters and significant conservation of network resources,

– reduction of necessary network traffic generated by higher layer network mechanisms, such as (in case of overlying IP network): DNS request-response, ARP broadcast request-response, etc.

To verify the proposed solution the already described simulation environment have been utilized, but instead of Mesh Gates, which are not present in this scenario, a number of IP application servers have been activated randomly through the MBSS. The results, presented in Figs. 4 and 5, compare maximum and average path lengths between an application client and its chosen server for IP-based server discovery method [8] and the proposed, cross-layer HLSA procedure.

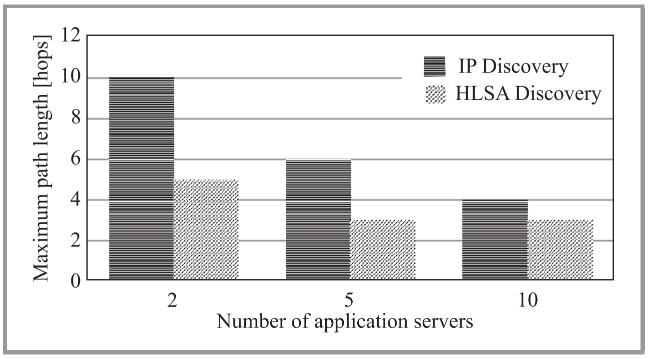

Fig. 4. Maximum client-server path length for IP and HLSA-based server discovery.

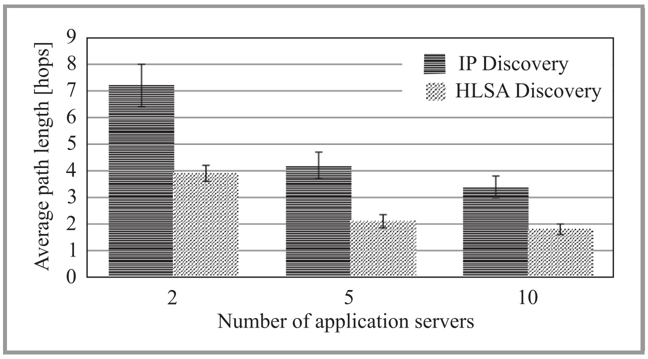

Fig. 5. Average client-server path length for IP and HLSA-based server discovery.

It can be seen, that IP-based discovery results in selection of more distant application servers, compared to the proposed solution, which provides clients with information necessary to select the server with the best Airtime Metric. The cause for this effect is a large number of factors (originating from both ISO-OSI layer 2 and 3 mechanisms) which impact relatively high-level IP-based communication quality assessment. Also, limited time which can be devoted to such on-demand assessment makes the result prone to errors caused by short-time fluctuations of path quality. It can be observed that the longer the distance between client and server, the more IP discovery is prone to errors and less predictable. On the other hand, Airtime Metric values for wireless links are calculated by mesh stations proactively and over longer periods of time, producing more reliable results. The use of proposed mechanism allows that information to be delivered to the client almost instantly. The proposed HLSA mechanism is clearly able to provide shorter paths, thus conserving network resources and providing better service to clients.
Additionally, as an example of advantages in initial service connection time provided by the solution, Table 1 contains a comparison of popular DNS-based service discov-

Table 1
Example IP-based and cross-layer server discovery procedure timings

Step	IP Discovery	Time	HLSA	Time
1 Service discovery	Broadcast ARP Request-Resp. (for predefined DNS server)	<1 s	Gathering/comparing HLSA announcements	100 – 800 ms
	DNS Query-Response (for SRV records)	<200 ms		
2 Server selection	Broadcast ARP Request-Resp. (for obtained set of 10 application servers)	$<1,5$ s		
	ICMP Test Request-Resp. (for obtained set of 10 application servers)	<5 s		
3 Server connection	Connection to server and initial, service specific handshake	<500 ms	HLSA assisted mesh path discovery	<300 ms
			Connection to server and initial, service specific handshake initiated by HLSA	<300 ms
	Total time	<8.2 s		<1.4 s

ery [9] and server selection method deployed in previously described, simulated IEEE 802.11s environment, with the proposed HLSA-based mechanism.

It should be noted, however, that the presented time values are highly dependent upon mesh structure and various network and service configuration parameters as well as network load, and, as such, should be threated only as an example.

Also, highly inefficient IP ARP resolution can be eliminated altogether by including appropriate layer 3/2 mappings in the HLSA messages. An optional inclusion of initial, service specific configuration parameters can allow further time gain, but will most often require a modification of server and client software.

6. Testbed Experiments

Due to clearly advantageous impact of proposed extensions of path discovery mechanisms on efficiency of mesh operation, a practical implementation of the described mechanisms have been created.

A standard Linux kernel 3.6.10-4 implementation of IEEE 802.11s mechanisms have been used as a base and extended with:

- additional topology control functions, aimed to disallow unnecessary formation of low quality mesh links in dense mesh environment,
- ability to form peering relationships between mesh gates through external, wired infrastructure,
- ability to utilize any mesh gate present for communication with external networks.

The implementation have been tested in testbed installation designed to verify the proposed solutions in IEEE 802.11s wireless mesh deployed in office building environment. For this purpose, twenty mesh stations have been activated in 50×15 m area of two subsequent floors of Faculty of Electronics, Telecommunications and Informatics of Gdańsk University of Technology. Of these 20 stations, 2 on each floor were designed as mesh gates connected to a common wired infrastructure. Stations utilized a single, least utilized at a time of each test run, frequency channel in 2.4 GHz ISM band and IEEE 802.11g transmission technology.

The test scenario involved a single, 5 minute long, TCP test transmission between a two randomly selected mesh stations located at least 15 meters apart, while 3 other such TCP connections provided background traffic. A selected number of standard mesh gates have been substituted with modified ones: 0 (standard IEEE 802.11s MBSS), 2, 3, and 4.

For each number of modified mesh gates the test has been performed 20 times during working hours and 20 times during nighttime, to help assess the impact of external system interference on our mesh installation. The state of wireless medium have been additionally monitored with use of physical layer analyzer, to detect potential anomalous conditions such as particularly strong interfering signals. The results, in form similar to these of simulation experiment (maximum and average MBSS path length and average throughput for test connection), are presented in Figs. 6 and 7.

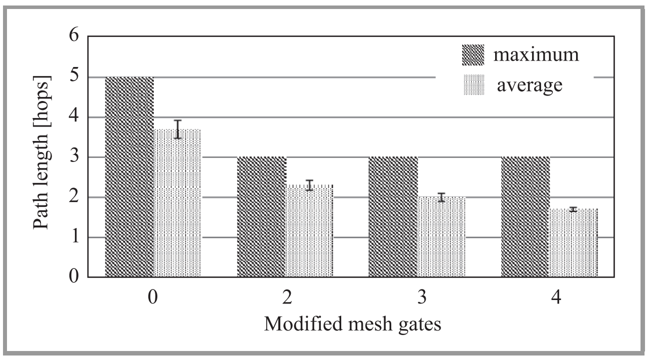

Fig. 6. Maximum and average path length for different number of modified Mesh Gates in testbed environment.

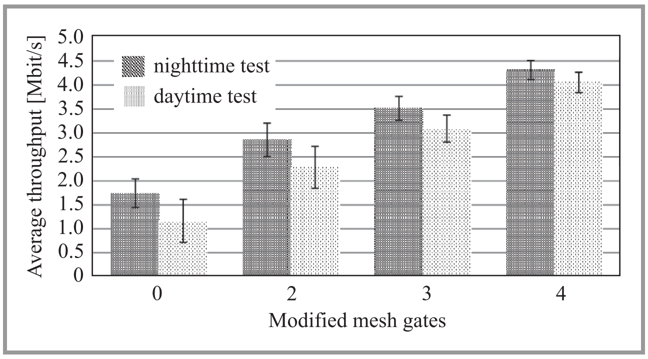

Fig. 7. Average test connection throughput for different number of modified Mesh Gates for daytime and nightime test in testbed environment.

Testbed installation is significantly smaller than the system previously considered in simulated scenario, which, combined with the fact that its node layout is fixed, results in more uniform path length results visible in Fig. 6. Despite the above fact it is evident, that simulation and testbed results show distinct similarities, confirming utility of the proposed solution. In both cases length of transmission paths through wireless domain is significantly shortened, which results in both higher and more stable throughput, as shown in Fig. 7. It can also be observed that external interference in testbed system is an important factor, resulting in reduced and less stable throughput. Unsurprisingly, the effect is more pronounced during working-hours, when external wireless system located in the area show significant activity, making it even more important to minimize path lengths through wireless MBSS.

7. Conclusions

All proposed extensions retain full compatibility with IEEE 802.11s standard, taking advantage of its inbuilt customization functions and concentrating rather on extending their scope of usage then introducing completely new solutions in place of already standardized ones. Proposed solutions can be generally classified as integration mechanisms, aiming to provide smooth network system operation across network and ISO-OSI layer boundaries.

Their basic functionality and efficiency have been verified by means of simulation model in sizable (100 nodes), self-organizing mesh deployment scenario and subsequently by testbed experiment in real-world environment. The results clearly indicate their expected utility in IEEE 802.11s mesh deployments, and further studies concerning their impact on specific applications performance are currently being conducted.

Presented solutions are part of an ongoing research concerning cross layer integration, interworking and mobility support for IEEE 802.11s-based systems.

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