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Broadband Internet Access via Multi-Hop Wireless Mesh Networks: Design, Protocol and Experiments

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Abstract While bandwidth for Internet access in urban areas is steadily increasing in recent years, many rural areas are still suffering from the effect of the digital divide. This paper presents a broadband Internet access paradigm developed in the context of the ADHOC-SYS project, which was financed by the European Commission under the 6th Framework Program Information and Society Technologies, within the strategic objective of *Broadband for All*. Aiming at providing reliable Internet access in rural and mountainous regions where xDSL connections are not available due to coverage limit, the ADHOCSYS network provides

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a cost-effective solution based on multi-hop wireless mesh network technologies. Starting from a general description of the network architecture and application scenarios, this paper focuses on presenting the routing, QoS and network deployment aspects of the developed solution. Other aspects like reliability prediction, power supply, security and authentication, and auto-configuration, etc are discussed only briefly. In order to validate the developed broadband access solution, a real-life operational wireless mesh network has been deployed in a mountainous region in Northern Italy. The performance of the developed solution has been evaluated based on the deployed real-life network, and the obtained numerical experimental results, along with the practical lessons learnt through installations and experiments are also presented in this paper.

Keywords Wireless mesh networks · Broadband access · Routing protocol · Real-life operational network · Implementation and experiments

1 Introduction

The continuous evolution of network infrastructure and networking technologies makes today's Internet far more robust and far more ubiquitous than it used to be 5 or 10 years ago. Bandwidth in urban areas is rapidly increasing, allowing the delivery of high bit-rate multimedia content and Quality of Service (QoS) demanding services such as Internet Protocol Television (IPTV) and Voice over IP (VoIP). However, broadband Internet connections and ubiquitous access in many rural and mountainous areas are still not a reality, and for this reason such areas are still experiencing the effect of the digital divide in terms of the types of services that they can receive and at which data rate these services can be accessed.

To provide broadband access to residential costumers, various technologies, such as optic fiber, twisted pairs, coaxial cables, Digital Subscriber Line (DSL), satellite communications, and wireless networks can be used, depending on specific service provider and location of the end-users. Although DSL appears as probably the most popular technology for broadband access in urban areas, it has its intrinsic limitations in rural and mountainous areas due to its very limited coverage. Wireless networks, e.g. IEEE 802.11 Wireless Local Area Networks (WLANs), on the other hand, exhibit obvious advantages over their wire-line counterparts. However, one-hop wireless networks are either costly and usually require channel licenses (e.g. 2.5G/3G cellular networks and licensed Worldwide Inter-operability for Microwave Access (WiMAX)), or have limited coverage (e.g. 802.11 WLANs).

In the physical environment envisaged by this work, such as rural and mountainous regions in Southern Europe, inhabitants are typically aggregated in few dozens of small towns, villages and farms that can be as far as several kilometers apart from each other. Consequently the project has considered situations where these end-users are not reachable by DSL connections or one-hop WLANs, neither for the time being nor in the near future, because people dwellings are spread so apart from towns or villages that cable laying becomes impracticable or at too high costs for operators [1].

The main objective of the ADHOCSYS project is to provide a reliable broadband Internet access solution to people who live in the aforementioned areas. This objective is achieved by means of the creation of a reliable multi-hop broadband wireless network, in a specially designed Wireless Mesh Network (WMN) form. The coverage of the WMN can be easily extended to cover targeted areas, in a multi-hop fashion.

Although significant efforts on mesh network experimentation have been made [2,3], recent deployments of mesh networks are mainly targeting at urban areas and/or university campuses. These environments are more friendly to network deployments, maintenance and operations since compared with their rural counterparts they are characterized by spatial node proximity, easier node accessibility, better weather conditions, shorter links, more aggressive electromagnetic scenarios, smaller network size, un-limited power supply, and higher investment budget availability. Furthermore, the hardware adopted, the routing protocols employed, the software installed and the security strategies used in these networks do not fulfill the requirements for deployment of such networks in remote areas. This is because such networks were built for research purposes and focus solely on specific scenarios as opposed to ADHOCSYS networks which are built to provide real-life operational broadband services in rural and mountainous areas as a cost-effective solution.

In this context, ADHOCSYS networks are organized in an ad hoc fashion through two-tier multi-hop wireless networks. The network provides end-users with access both to a minimum set of services such as e-mail, web browsing services and to higher level services such as high bit rate multimedia contents and IP Telephony. As an enhancement to the state-of-the-art technologies in multi-hop wireless networks, an extended version of the Optimized Link State Routing (OLSR) protocol [4] with new features has been implemented, and a pragmatic approach for QoS provisioning in such networks has been proposed. Other aspects of the designed network including auto-configuration, self-healing, security and authentication, power supply, reliability prediction, remote system status monitoring, etc have been procured. The implemented codes have been released publicly through the General Public License (GPL).

The rest of this paper is organized as follows. Sect. 2 gives a brief introduction to the architecture and characteristics of the designed wireless mesh network. Sect. 3 describes the designed enhancements to the OLSR routing protocol while the proposed QoS approach is presented in Sect. 4. The implementation and deployment of a real-life operational WMN are presented in Sect. 5, together with the experimental results. Finally, the concluding remarks are given in Sect. 6.

2 Network Architecture and Characteristics

In the following, we present briefly the network architecture and system characteristics of the broadband access solution developed in the ADHOCSYS project.

2.1 Network Architecture

The size of a WMN network might be large in terms of both geographic expansion and the number of nodes. Therefore a hierarchical architecture is proposed to allow the network scale from a few nodes to several hundreds, or even more nodes. Figure 1 illustrates the ADHOCSYS network architecture with a 2-tier hierarchy. The two-level hierarchical structure has been designed in order to decrease system complexity while keeping network scalability at the same time.

As shown in the figure, the network is composed of a number of access networks connected through backbone nodes. The first tier is a backbone network composed of multi-hop connections with long distance wireless links connecting to several access networks. The backbone links are typically based on 802.11a links, and long distances between transmitters and receivers are achieved through directional antennas. Depending on local regulations, WiMAX could also be used to form the backbone. The second tier is a mesh access network

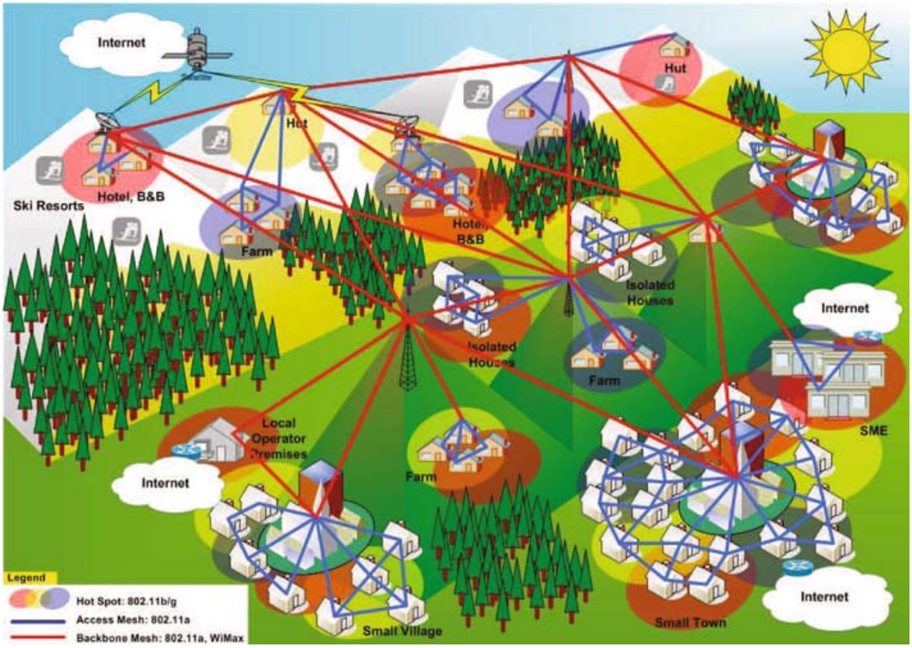


Fig. 1 Illustration of ADHOCSYS network architecture and a typical application scenario, with the first tier backbone network in *red* and the second tier mesh networks in *blue*

with short wireless links composed of a set of connected Mesh Routers (MRs) which serve as Access Points (APs) for end-users. The connections between MR/APs and end-users are typically based on 802.11a/b/g links and their frequencies are not overlapping with the ones used in the backbone network. The backbone and access networks themselves are based on static topology however the network exhibits ad hoc features. As the clients of this network, the end-users can be either static (typically home users) or nomadic (typically visitors).

In brief, there are three categories of nodes in the proposed network architecture:

1. *Backbone nodes*: wireless devices used for backbone networks. Backbone nodes take part in routing.
2. *Mesh routers*: wireless devices used for mesh networking and serve as APs for end-users. Mesh routers take part in routing.
3. *User equipments*: client equipment such as PCs, laptops, PDAs, wireless tablets etc. User equipments are owned by either home users or visitors and do not take part in routing.

The hardware and software features of these three node types are summarized in Table 1. In addition to those three types of nodes, gateway nodes need also to be deployed in an ADHOCSYS network. A gateway node, which provides the connection between the Internet and the WMN, can be configured either from a backbone node or from a mesh router, by upgrading the node with an enhanced gateway functionality module (hardware and/or software). The gateway nodes are characterized by at least two interfaces, with wired connection towards the fixed Internet and wireless connection towards the wireless mesh network. As illustrated in Fig. 1, multiple gateway nodes are preferably installed, in order to achieve the benefit of multi-homing, for example, higher reliability, multiple routes, and load balancing.

Table 1 Typical ADHOCSYS mesh router configurations

	Backbone node	Mesh router	User equipment
Hardware			
Antenna	Directional (up to 28 dBi gain) or Omni-directional (6–8 dBi gain)	Omni-directional (6–8 dBi gain)	Omni-directional (3 dBiS gain)
Location	Outdoor (valley)	Outdoor (roof)	Indoor/outdoor
Power supply	220 V power supply. May be battery powered	220 V power supply. Some nodes may need battery power supply	220 V power supply, 12 V (e.g. car adapter), or battery—powered
Radio channel	5 GHz (IEEE 802.11h) or 3.5 GHz (WiMAX)	5 GHz (IEEE 802.11h) or 2.4 GHz (IEEE 802.11b/g)	2.4 GHz (IEEE 802.11b/g)
Radio card slot	At least 2 × MiniPCI	At least 2 × MiniPCI	PCMCIA, PCI, USB
Business model	Business market	Consumer market	Consumer market
Software			
Wireless mode	Ad hoc mode interface	Ad hoc mode and AP mode interfaces	Client
Wireless configuration	Automatic or assisted	Automatic or assisted	Manual
IP configuration	Static	Static/dynamic	Static/dynamic
Routing	Hierarchical OLSR with ADHOCSYS enhancements	Hierarchical OLSR with ADHOCSYS enhancements	Do not participate in routing. Use MRs as default gateways

2.2 System Characteristics

Various aspects have been considered in the designed network, from the perspective of providing a reliable working solution in the above mentioned architecture. Compared with other existing or upcoming multi-hop wireless mesh networking technologies, like the ones described in Refs. [1,5], the ADHOCSYS networks exhibit several salient characteristics as presented below. The salient characteristics of the developed solution are briefly presented in the following. In Sects. 3 and 4 the routing and QoS aspects, as the main focus of this paper, will be described in more details.

- *Reliability prediction*. A model to predict network availability in order to ensure that the reliability requirement is fulfilled for a given network configuration has been proposed. Given an expected reliability level for each node and link, the expected availability of the network is computed. This calculation helps to identify how many redundant nodes or channels are required in order to serve a given number of users with high enough availability. More details about this aspect can be found in Ref. [6].
- *Multi-homing with load balancing*. Multi-homing allows more robust network connections since the Internet services are still available when at least one of the multiple gateways is functioning. In addition, load balancing among gateways can be achieved when the network is multi-homed with multiple gateways.
- *Multi-path with metric-based routing*. Among multiple available paths between a specific pair of source and destination, the best path will be selected depending on metric-based routing table calculations. In case of a link break or path failure, an alternative path can be obtained immediately.

- *Multi-channel with channel selection*. The multi-channel function is supported by nodes equipped with multiple wireless cards (typically 2∼4 cards, depending on the role of a node). It provides both channel redundancy and higher per-hop throughput when installed. Channel selection happens between any two of the above mentioned three node types. A central-controlled algorithm has been developed where each node measures and reports the interference level in its neighborhood, and based on this information, a central channel manager decides the most suitable channel for each pair of nodes.
- *QoS provisioning*. QoS preference in ADHOCSYS networks has been given to a set of essential services. This approach differs from the conventional QoS definition that relies mainly on delay tolerance for traffic flow classification, since providing a basic set of services is regarded as of highest priority in this project. The proposed solution can however be customized by configuring a different set of essential services.
- *Security and authentication*. Techniques using captive portal for granting web-based authentication access and using IEEE 802.1X for granting port-based authentication access have been used to authenticate end-users. In order to ensure secured communications between backbone nodes and mesh routers, as well as among mesh routers, authenticated routing messages have been designed and implemented.
- *Power awareness*. Since nodes in both backbone and access networks could be battery-powered, techniques for designing stand-alone photovoltaic power supply systems have been developed and an operational stand-alone photovoltaic system has been implemented. Additionally, techniques for reducing power consumption and increasing energy efficiency of the overall system have been investigated. Moreover, a power-aware plug-in to the OLSR protocol using an estimation of the battery level of each mesh router has been implemented.
- *Auto-configuration and IP address allocation*. Private addresses with Network Address Translation (NAT) have been used in our design. In brief, two sets of private addresses have been used, one for AP-to-AP connections and one for AP-to-Client connections. Typically, $10.x.y.z$ with appropriate netmask is used for AP-to-AP connections and $172.16.x.y$ with appropriate netmask is used for AP-to-Client connections. Furthermore, the address assignment process and node operation statistics can be remotely controlled and monitored by a central controller which is located at the system administration office.

3 Routing in ADHOCSYS Networks

3.1 Routing Protocol Considerations

Inherited from ad hoc routing protocols, the routing strategies in WMNs can also be classified as reactive, proactive or a hybrid of them. Although reactive protocols generate less overhead in general, they cannot provide instantaneous node and link status information since no messages are exchanged among mesh routers if there is no user data traffic. This means that reactive routing protocols cannot provide real-time network availability information to system administrator, which is crucial from reliable service provisioning point of view. Therefore, the most representative proactive ad hoc routing protocol, OLSR, has been selected as the baseline protocol for developing our routing strategy in ADHOCSYS networks.

Another reason for selecting OLSR is because of its legacy inter-network connection capability using Host and Node Association (HNA) messages. With this message, a gateway node is able to advertise its Internet reachability to all other nodes, so that they can access

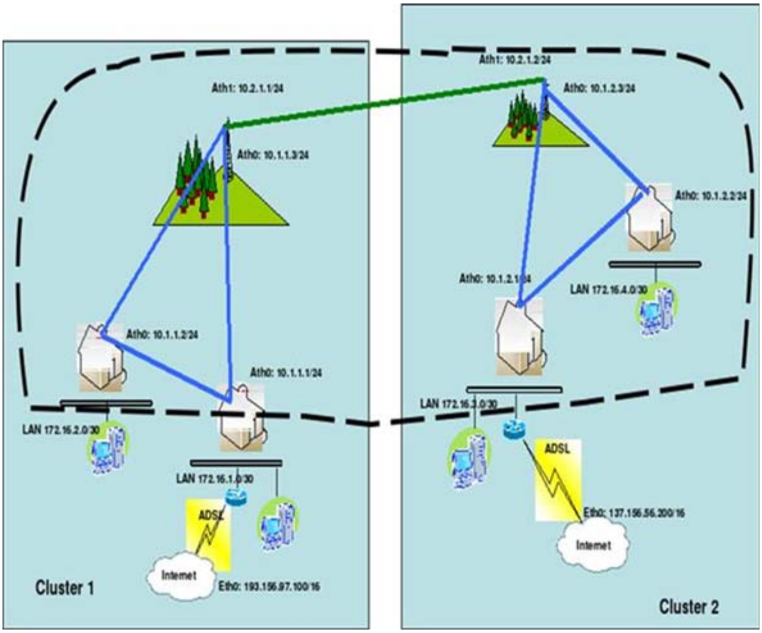


Fig. 2 Hierachical OLSR illustration

the Internet through the gateway. It is worth mentioning here that even though Radio-Aware OLSR has been excluded in the newest version of the IEEE 802.11s mesh networking standard [5], the function of HNA has been integrated as part of the Hybrid Wireless Mesh Protocol (HWMP) in 802.11s.

However, the hop-count based OLSR specified in Ref. [4] is not able to fulfill the requirements for our targeted network. Therefore, a number of enhancements to the legacy OLSR protocol have been designed within the project, as presented in the following subsections. The enhancements have also been implemented and deployed in real-life WMNs, as to be presented in Sect. 5.

3.2 OLSR Enhancement: Hierarchical Structure

There are two levels of hierarchy according to our network design where Level-1 hierarchy corresponds to connection among backbone network nodes, while Level-2 hierarchy corresponds to connection among mesh routers in access networks. An access sub-network which is connected to other access sub-networks is referred to as a cluster. A backbone node serves as the cluster-head and advertises its reachability to other clusters periodically. The cluster-heads are predefined, thus there is no need to develop an algorithm for cluster-head selection. Figure 2 illustrates an example of such a network with two clusters. In addition to these two tier hierarchy, gateways to the Internet can be connected directly either to the first tier or to the second tier.

The cluster-heads are aware of each other, and are connected to each other, either directly or via multi-hop relays. The latter case corresponds to a situation in a long valley, where the intermediate nodes are statically configured as relays. The cluster-heads aggregate IP addresses in each cluster and are responsible for communications between clusters. HNA

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Network Address                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                            Netmask                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    GW Status Value    |    Reserved     |  GW Metric Type     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Network Address                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                            Netmask                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    GW Status Value    |  Reserved       |GW Metric Type       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                              ...                              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Fig. 3 Illustration of the extended HNA message format

messages are used for disseminating both the Internet gateway information and the connectivity information among different network clusters. More specifically, each cluster-head uses HNA to advertise its reachability for both sides:

- Inter-cluster HNA message advertises a cluster-head's connectivity of all nodes, including both mesh routers and Internet gateway nodes inside the same cluster, to other clusters. This message is sent to all other connected cluster-heads using unicast packets (note this is different from the standard version of OLSR), or subnet-directed-broadcast packets. Both the mesh router and the gateways are advertised as connected subnets, specified by the netmask field in HNA.
- Intra-cluster HNA message advertises a cluster-head's connectivity to other clusters, including also Internet gateways from another cluster. This message is sent to all mesh routers inside the same cluster. Both mesh routers and gateways from another cluster are advertised as connected subnets, and are specified by the netmask field in HNA.
- For both inter-cluster and intra-cluster HNA messages, an extended HNA format (see Fig. 3) has been used, so that metric-based routing can be used for gateway selection of any mesh router. Various metrics, for instance, the airtime metric, can be used in our implementation [7]. Moreover, every mesh router in a cluster is advertised as a special type of *gateway*, in which it acts as an AP for its clients, and therefore it generates HNA messages as well. The cluster-head, upon receiving this information, establishes an HNA Information Base, which is then used for building the inter-cluster HNA messages to be forwarded to other cluster-heads.

3.3 OLSR Enhancement: Multi-homing with Load Balancing

HNA messages in OLSR allow gateway nodes to announce their network association (network address and netmask) with the Internet to other OLSR nodes. When multi-homed, the gateway which is closest to the end-user, in terms of the number of hops, is always chosen as the default gateway by the legacy OLSR. The other gateway will be used only if the default gateway is down, and the process of finding another gateway may take up to a few seconds with the default parameter settings in Ref. [4].

With the implemented multi-homing enhancement, a node uses a metric-based policy to select the best gateway. These metrics include for example link and path capacity, traffic load

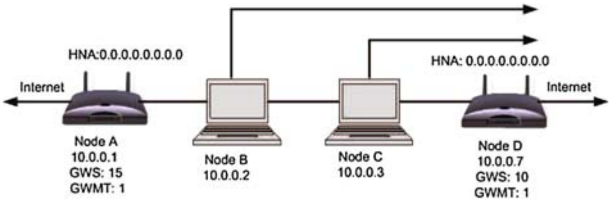


Fig. 4 An example of multi-homing with load balancing

and other QoS parameters, in addition to the number of hops. As illustrated in Fig. 3, the HNA messages have been modified to carry such information in the gateway advertisement. Furthermore, the routing table calculation process has been improved so that the second gateway is immediately available once the first (default) gateway is down.

Furthermore, three types of load balancing have been considered in our network, namely load balancing among channels, paths and gateway nodes. Given that two or more channels co-exist between a pair of nodes, if one channel is close to congestion, another channel should be used. Similarly, if one path is over-loaded, the routing table calculation process will re-calculate a new path. This is triggered by including the traffic load information in a newly defined LINKINFO message, which has been implemented in a plug-in to OLSR. For multi-homed network, the traffic load status is monitored at each gateway and is disseminated to other nodes inside the network, using again the modified HNA message. Once this information is available at each router, the router could re-route its traffic towards a less-loaded gateway. This process needs to be carried out periodically so that the traffic load through the whole network is balanced among available gateways.

Figure 4 illustrates a simple example of the designed multi-homing function with load balancing among gateways, in which a node is able to choose its default gateway on advertised metrics, instead of on the number of hops. In this network, each mesh router or gateway monitors its traffic load status periodically, and this information is flooded to all mesh routers by LINKINFO. Upon receiving such messages, each mesh router maintains a database of link load and gateway load information, as the metric for route calculation. If a given path becomes saturated or close to congestion, the load balancing mechanism will re-establish a new path. For instance, Node B will usually choose Node A as its gateway. If this path is over-loaded, a new gateway Node D will be selected via path B-C-D, even though the number of hops to D is greater.

3.4 OLSR Enhancement: Multiple Interfaces

In the legacy OLSR protocol, the Multiple Interface Declaration (MID) message is used when a node has several interfaces, but only a single interface is selected as the main (working) interface. That is, only one interface will be used for path establishment.

With the implemented multiple interface enhancement, each individual interface is treated independently and multiple interfaces can work at the same time. That is, more than one link can be established between two neighbouring nodes when they are equipped with more than one interface. As a consequence, the following benefits are achieved:

- Higher reliability: if one link is down, a node with multiple interfaces could still provide routing path for end-users. For instance, when equipped with two interfaces (two wireless cards operating on two non-overlapping channels simultaneously) between a pair of nodes, the link between these two nodes is still available even if one of the two channels is broken.

- Higher throughput: multiple interfaces can also be used jointly to form a common channel which provides higher link capacity. For instance, with two interfaces established between two neighboring nodes in a real-life mesh network, we have achieved higher throughput, twice as high as that of the single interface case, or even higher.

Different from the legacy OLSR, every individual interface is regarded as a main address in our design. In its HELLO exchange, each interface advertises other interfaces co-located on the same router as its neighbors. To other routers in the network, the advertised two interfaces look like two distinct nodes. The multiple interface information is further disseminated inside the mesh network through topology control messages. As a consequence, two or more paths can be established between two neighboring routers and to the gateways.

3.5 OLSR Enhancement: Cross Layer Link Layer Notification

When a link break happens, the legacy OLSR will observe and react to this change by exchanging HELLO and topology control messages and this process may take up to a few seconds. With link layer notification, a new path, if existing, will be available immediately (e.g. in the order of milliseconds) after a link break. With this enhancement, we are able to provide the end-users with non-interrupted access.

The basis for this enhancement is to utilize link break information gathered at the MAC layer to impose OLSR routing table re-calculation. More specifically, the MAC layer detects the link break and sends an indication to the protocol layer. Upon receiving such an indication which is treated as a topology or neighbour change, OLSR shall conduct routing table re-calculation immediately. More details on this enhancement can be found in Ref. [8].

3.6 OLSR Enhancement: Metric-Based Routing Table Calculation

The OLSR enhancements described above, as well as a few others such as power-aware routing, are based on an enhanced routing calculation algorithm, which allows us to use metrics for route computation. As the input of this algorithm, the *cost* of each link within the network will be advertised throughout the whole network so that each router has the topology and metric information needed for its routing calculation. The link cost could be data rate, delay, load status, or any other metrics of interest. Based upon this link cost information, a router is able to build its routing table according to the minimal path cost criterion similar to the Dijkstra's algorithm.

The developed algorithm works independently, regardless of the number and type of metrics that are adopted. This metric-based routing algorithm allows also the use of multiple metrics at the same time, and to assign a relative weight at each of these metrics. For a given network, which metric(s) will be used and its/their relative weight(s), are specified by the network administrator through a configuration file. Based upon this information, each mesh router is able to build its routing table according to the least-cost path selection criterion.

4 QoS Approach in ADHOCSYS Networks

4.1 QoS Considerations

The provision of an essential set of services to all end-users is one of the fundamental requirements of any approaches aimed at bridging the digital divide. An essential set of services on which today's Internet is based includes typically e-mail and web browsing services. Providing these services is therefore deemed as the highest priority of the QoS policy developed in the context of ADHOCSYS. Following this consideration, all other services, included advanced services such as high quality video streaming and IP telephony, are regarded as lower priority traffic. In addition, since the QoS requirements of these advanced services are usually very stringent, they can be provided under specific conditions, depending on particular network deployment scenarios. With this perspective, special mechanisms should be implemented to avoid potential unfairness of the QoS policy, which shall provide the users with as many advanced services as possible, but without affecting the essential set of services. The possibility of making emergency calls is another advanced service of primary importance in the designed network. Such service, where available, shall be provided at the highest priority.

All the aforementioned aspects have been considered in the proposed QoS solution. The novel approach to classification and prioritization of traffic flows adopted in ADHOCSYS is proposed in Subsect. 4.2, while the implemented algorithms and mechanisms are described in Subsect. 4.3 Other mechanisms, which have been implemented in the proposed solution but are not discussed herein, include flow identification, buffer management and queuing disciplines, traffic load measurement and Connection Admission Control (CAC).

4.2 Traffic Class Definition

The proposed QoS policy is based on the idea of categorizing traffic flows into various Traffic Classes (TCs). Each TC groups applications with similar requirements (e.g. streaming video, routing messages). Correspondingly, each traffic flow will receive different queuing service according to the buffer management and scheduling policy defined for the TC it belongs to.

According to our TC definition, each traffic flow is categorized into one of the following eight TCs.

- *Class I*: applications which require strong latency constraints and low bandwidth such as VoIP and chatting applications (jabber, Yahoo! Messenger, etc).
- *Class II*: applications requiring high throughput such as transaction-processing applications.
- *Class III*: essential set of services - interactive and best-effort type applications like web-browsing and e-mail.
- *Class IV*: routing and battery information.
- *Class V*: emergency calls.
- *Class VI*: high throughput and latency constraint such as streaming video.
- *Class VII*: Peer-to-Peer (P2P) applications.
- *Class VIII*: other types of traffic (unclassified).

TCs I, II, III from the above definition are based on the conventional QoS classification which relies mainly on delay tolerance of different service classes. TCs from IV to VII have been defined in order to allow finer service differentiation policies and to give priority to critical traffic classes such as routing messages and emergency calls.

One major difference between the proposed QoS definition and the conventional QoS definition is related to the different treatment for high bandwidth-demanding multimedia applications. As mentioned in the beginning of this section, this difference is caused by the re-definition of high priority from network layer constraints to service availability. While the conventional QoS paradigm puts high-bandwidth low-delay multimedia applications in

Table 2 Mapping between application classes, application categories and WMM access categories

HTB AC	TC	WMM access category
C	II, VII, VIII	0 (Best effort)
B	I, VI	1
A	III	2
A, B	IV, V	3 (Highest priority)

the second highest priority class immediately below low-bandwidth low-delay applications (corresponding, for example, to the AC_VI and AC_VO classes respectively in the vision of 802.11e/Wireless Multimedia (WMM)), TC_VI applications are allocated to a lower priority class in our context. In other words, while the conventional QoS definition focuses solely on delay sensitivity of an application, we have further considered bandwidth requirement of an application, in addition to its delay sensitivity, in our TC definition.

4.3 QoS Mechanisms and Implementation

Since hard (deterministic) QoS can only be provided by means of the IEEE 802.11 family of standard protocols [12] at the expense of high loss in channel efficiency [13], the proposed solution resorts to a combination of WMM [14] and Hierarchical Token Bucket (HTB). WMM, the mostly wide spread implementation of the IEEE 802.11e standard, provides inter-node soft (probabilistic) QoS, while HTB, implemented in the kernel of the Linux Operating System, is able to provide hard intra-node QoS. The combined solution delivers a more efficient use of the wireless channel through WMM while guaranteeing hard QoS constraints by means of HTB. A congestion control mechanism is then applied to traffic class based on measured traffic load.

To better exploit the functionalities of the HTB mechanism, the traffic classes have been further categorized into three Application Categories (ACs). The essential services for both users and networks are inserted in AC A. AC B groups flows with strict delay constraints, while AC C groups high-bandwidth demanding (but not essential) applications and un-categorized flows. Table 2 shows the mapping between application categories, application classes and WMM ACs. The differentiation mechanism implemented in the HTB tree is also presented in the same table.

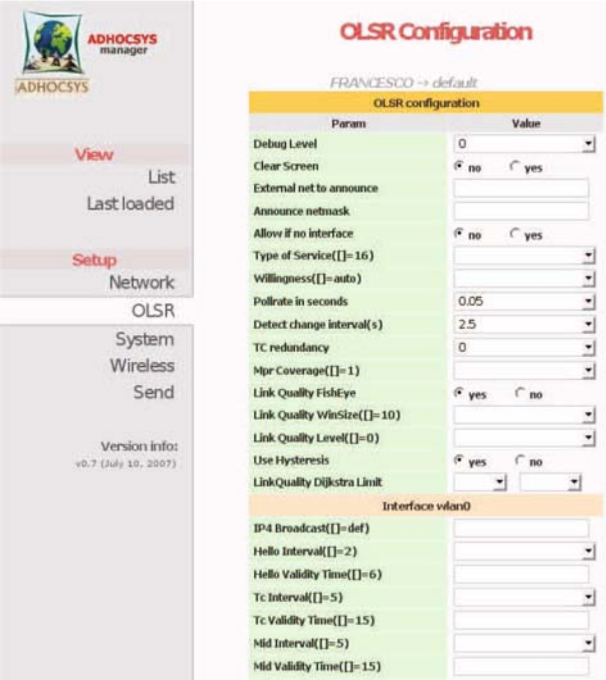
Furthermore, since the proposed QoS policy is not node-based, but flow-based, traffic flows generated or received by the same end-user may belong to different classes, as time varies. Therefore, for QoS class priority definition, the precedence has been given to traffic flows belonging to TC III services, in normal conditions. When emergency calls occur, nevertheless, priority will be given to TC V traffic.

5 Implementation, Deployment and Experimental Results

In this section, we present briefly the implementation of the proposed solution, and the deployment of a real-life WMN network for Internet access. The experimental results obtained based on the developed solution are also presented.

5.1 Implementation Brief

The OLSR enhancements described above, as well as the other features developed by the ADHOCSYS project have been implemented, converted to a software image and installed in



OLSR Configuration

FRANCESCO -> default

OLSR configuration	
Param	**Value**
Debug Level	0
Clear Screen	● no ○ yes
External net to announce	
Announce netmask	
Allow if no interface	● no ○ yes
Type of Service([]=16)	
Willingness([]=auto)	
Pollrate in seconds	0.05
Detect change interval(s)	2.5
TC redundancy	0
Mpr Coverage([]=1)	
Link Quality FishEye	● yes ○ no
Link Quality WinSize([]=10)	
Link Quality Level([]=0)	
Use Hysteresis	● yes ○ no
LinkQuality Dijkstra Limit	
Interface wlan0	
IP4 Broadcast([]=def)	
Hello Interval([]=2)	
Hello Validity Time([]=6)	
Tc Interval([]=5)	
Tc Validity Time([]=15)	
Mid Interval([]=5)	
Mid Validity Time([]=15)	

Fig. 5 Illustration of the enhanced OLSR configuration interface

mesh routers built on Mikrotik Routerboard [10]. The implementation is based on an open source implementation of OLSR [9], and the implemented codes have been released and are available upon request. As an excerpt of our implemented solution, we illustrate in Fig. 5 the configuration interface for OLSR parameter setting which shows the configuration for each backbone node and mesh router. The configuration profile for each node can be accessed and modified remotely through a central control tool as part of the system administration.

5.2 A Real-Life Network

In order to prove the effectiveness and the applicability of the developed multi-hop broadband access technology, we have deployed a real-life operational network in a mountainous region located in Northern Italy, called *Comunità Montana Valle Sessera* (Valle Sessera Mountain Community). Figure 6 illustrates the outlook of the whole network and Fig. 7 illustrates the access network where nodes in Fig. 7 mean MRs/APs in this village.

The deployed real-life WMN provides broadband Internet connection to inhabitants in the village which is located about 12 km from an Asymmetric DSL (ADSL) gateway. The backbone links in this network are formed with 802.11a connections with directional antennas. As illustrated in Fig. 6, the longest per-hop link is 7 kilometers. The access networks are using 802.11a/b/g links with omni-directional antennas, and the distances between each pair of mesh routers shown in Fig. 7 range from 100 m to 460 m. Any end-user covered by an AP can connect his/her PC or home network to a node Ethernet port to have wireless access to the Internet.

The access network consists of 10 mesh routers, covering the whole village with an area of approximately 1,900*650 sm, and is connected through multi-hop backbone nodes to the

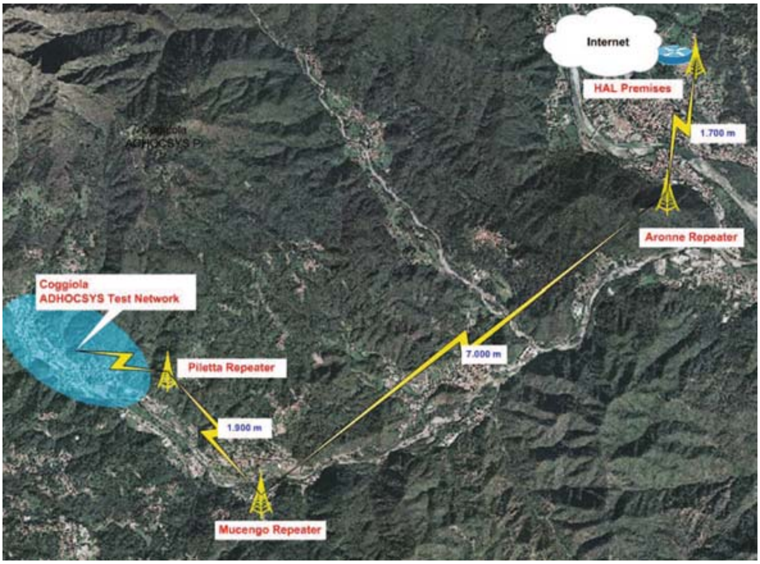


Fig. 6 ADHOCSYS real-life network: the whole picuture

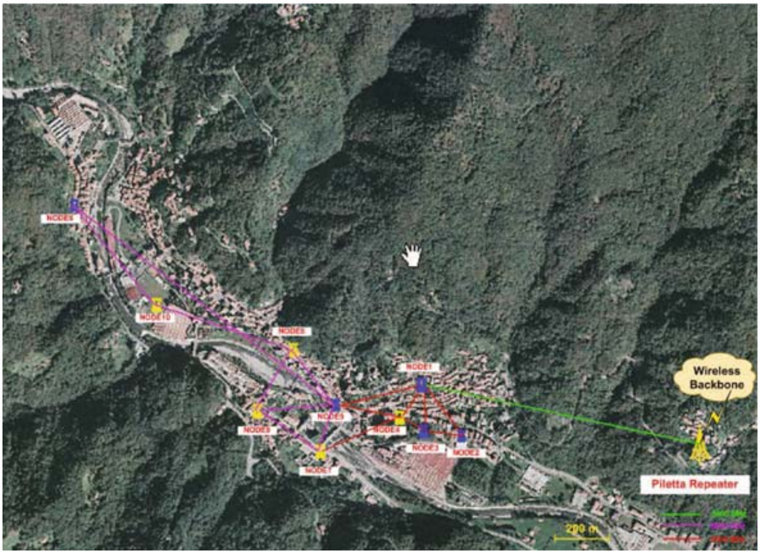


Fig. 7 ADHOCSYS real-life network: the access network

Internet gateway, as shown in Fig. 6. All backbone nodes and mesh routers run Linux OpenWRT operation system, based on a selected hardware platform [10]. The enhanced OLSR and other implementations have been converted into a Linux image and installed on these nodes.

5.3 Experimental Results

To validate the performance of the implemented solution, we have conducted a set of testing activities, and the results are summarized below. Due to the difficulty of setting up dozens

You are connected to adhocsys.org.

Network Name: adhocsys.org
Speed: 54.0 Mbps
Signal Quality: Excellent
IP Address: 10.16.17.7

Wireless Networks (5)

adhocsys.org Connected
www.wicadsl.it
<SSID not broadcast> This network has security enabled
<SSID not broadcast> This network has security enabled

To manage profiles of previously connected wireless networks, click the Profiles button.

Fig. 8 Internet access interface for an end-user

up to one hundred nodes in real-life, the overhead comparison result presented below is obtained through simulations using ns2. All other results are obtained from the real-life network described in this section.

5.3.1 Internet Access Availability and Path Throughput

Various locations have been tested within the coverage of the access network. The results demonstrate that the authenticated users, both home users and visitors, are able to enjoy diverse Internet services through the deployed multi-hop WMN. Figure 8 illustrates a typical access interface when an end-user covered by one of the mesh routers is connected to the WMN. After authentication, the user is able to access the global Internet for various types of services.

As shown in Fig. 6, the backbone network is composed of a three-hop path operating at 5 GHz. The per-hop link throughput for the backbone network is around 25 Mbps. For access network connections, we use 802.11a/b/g with *automatic link rate adaptation* since it results in better network connectivity. Even through the nominal link data rate is 54 Mbps, we observe that in most cases a lower, or much lower, data rate is adopted due to auto-rate adaptation. Depending on factors like the distance between the end-user and the AP, the distance between two mesh routers, the number of simultaneous connections as well as their traffic types etc, the per-link and multi-hop path throughput and latency vary according to different configurations. In Table 3, we give an excerpt of the measured performance for a few multi-hop paths within the access network, for both User Datagram Protocol (UDP) and

Table 3 Performance of the multi-hop MWN access network: data rate used, measured throughput and end-to-end delay

Test description (MRs)	Distance between (m)	Frequency (MHz)	Negotiated data rate (Mbps)	Multi-hop throughput (Kbps)	Average end-to-end delay (ms)
Traffic type:					
UDP					
3-hop: MRs 2-4-7	320–180	2,437–2,437	5.5–5.5	1,009	17.2
3-hop: MRs 2-4-7	320 –180	2,437–5,500	5.5–5.5	2,255	8.2
4-hop: MRs 2-3-4-7	120–200–180	2,437–2,437–2,437	5.5–5.5–5.5	768	21.6
TCP					
3-hop: MRs 7-4-2	180–320	2,437–2,437	5.5–5.5	1,041	
3-hop: MRs 7-4-2	180–320	5,500–2,437	5.5–5.5	1,674	
4-hop: MRs 7-4-3-2	180–200–120	2,437–2,437–2,437	5.5–5.5–5.5	710	

SPEEDTEST.NET
1/4/2008
4:34 PM GMT
DOWNLOAD
1020 kb/s
UPLOAD
820 kb/s
ISP: Fastweb
Server: Rome
Ping: 76 ms
Distance: ~ 350 mi

Fig. 9 Snapshot: access speed from a WMN end-user to a server in Rome

Transmission Control Protocol (TCP) traffic. It can be easily observed that higher throughput is achieved when two neighboring links are operating on two different channels.

Furthermore, we have also tested the access speed from end-users towards the global Internet. Again, the measured results depends on a few factors mentioned above. Typically, the measured access speed ranges from a few hundred Kbps up to 2 Mbps. Figure 9 illustrates a snapshot from an end-user within the deployed WMN towards a server in Rome.

5.3.2 OLSR Enhancements

This subsection summarizes the measured performance of the enhanced OLSR, in comparison with the original OLSR.

- Metric-based routing table calculation. The metric-based routing is activated using an Extend Routing Calculation (ERC) plug-in in which the type of the metric(s) as well as its/their weight(s) in routing table calculation can be specified. We have tested several different metrics such as link traffic load, or battery level and the resulted routing table shown by *traceroute* demonstrate that using the enhanced OLSR, a path with *least cost*, instead of minimal number of hops, is preferably selected.

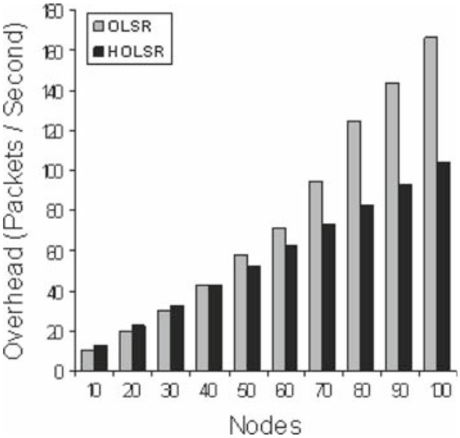


Fig. 10 Overhead comparison as a function of node population: OLSR versus HOLSR

- Overhead comparison: OLSR versus HOLSR. As shown in Fig. 10, in networks with fewer than 40 nodes, the flat OLSR routing protocol has slightly lower overhead of routing messages. From 40 nodes and above, the overhead in OLSR protocol grows substantially whereas with HOLSR it grows gradually. All functions of OLSR are still kept in HOLSR. This result indicates that the benefit of employing HOLSR occurs when the mesh router population is larger than 40. This value could be lower when the number of clients increases in a mesh network.
- Multi-homing with load balancing. Two mesh routers are configured as gateways in this test. In normal conditions, each router will choose the closest gateway as the default gateway. We then increase traffic load toward the default gateway by using a traffic generator, Iperf [11]. As a consequence, the default gateway will be switched to another gateway when traffic load has reached a given threshold. Another set of test on load balancing shows that when a link is close to congestion, it will be excluded from path section, so that traffic load among paths is balanced.
- Multiple interfaces. The multiple interface enhancement has been tested in a sub-net of the real-life network with three routers, each equipped with two wireless cards. It is observed that the throughput between nodes connected with two interfaces is twice as high as, or higher than the single interface case. For reliability test, we manually switched down one of the two interfaces while a session is undergoing, and the result indicates that much less packet loss is observed in the two interface case.
- Link quality detection and link layer notification. To monitor the quality of each link, the *iwspy* tool is adopted. The link quality detection is tested using a sub-net with three routers in the real-life network, as shown in Fig. 11. With the legacy OLSR which always chooses the shortest path, i.e. the one-hop path directly connecting MR7 and MR2, 25% packet loss has been observed. However, with the enhanced OLSR, the two-hop path between MR7 and MR2 via MR3 will be preferably selected and only 3% packet loss has been observed. The round-trip time in these two cases are also measured, respectively as 39.8 ms for the one-hop case and 37.4 ms for the two-hop case. This is because that the per-hop link data rate in the latter case is much higher than that of the one-hop case.

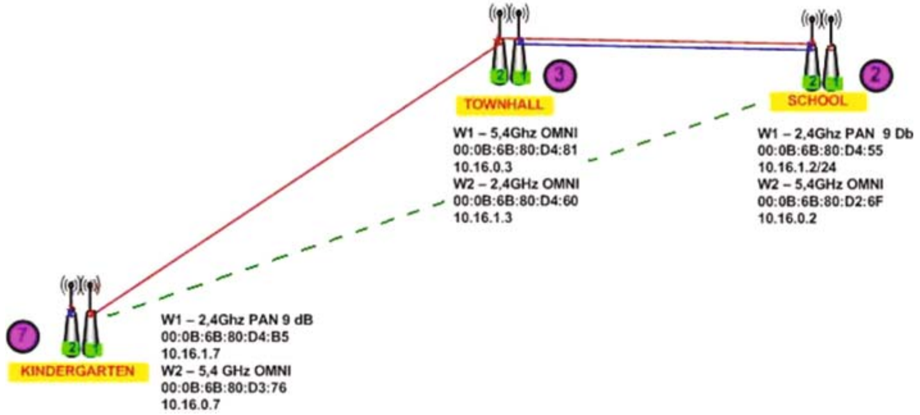


Fig. 11 Test configuration of link layer notification

5.3.3 Link Instability

We observed link instability in various situations. For example, the leaves of the trees in summer time could lead to poorer link quality among mesh routers, resulting poorer access satisfaction among end-users. Correspondingly, a real-time link monitoring tool for link quality has been developed, through which the system administrator is able to monitor and observe whether a link is up or down 24-h a day, remotely through a website accessible from anywhere. A periodic link availability statistic can also be obtained from this tool.

Regarding link stability, we have also compared the performance of the legacy OLSR with the enhanced OLSR. Again, auto-rate adaptation is enabled for each node in this test. With the hop-count based OLSR, the paths become very unstable since once the destination node is reachable through a lower hop-count path the new path will be selected. For example, the direct link between MR 7 (kindergarten) and MR 2 (school) in Fig. 11 is quite unstable (it represents that these two MRs may have direct connection at the lowest data rate and this link can switch between up and down in the order of milliseconds, depending on traffic and environmental factors). With the legacy OLSR, the direct path will only be selected once this link is up, and the two hop path will be used if the direct link is down. As a consequence, the path between these two MRs jumps between these two alternative paths back and forth quite often. This path instability has serious negative impact on the service continuity of the end-users. When the enhanced OLSR is used in this case, however, the path between these two MRs becomes much more stable, via the two-hop path. This is because that the cost metric developed in our enhancement would lead OLSR select the more stable path, as MR 7 (kindergarten) ↔ MR 3 (townhall) ↔ MR 2 (school).

5.3.4 QoS Performance

The proposed QoS strategy exhibits an average delay close to T1 DSL connection in the order of 15 ms with delay performance for 95% of the users in the range of 27 ms. The most interesting aspect observed is the stability of the performance both in periods where the different traffic flows overlap and during periods where the traffic flows operate in isolation. As illustrated in Fig. 12, a mechanism that dynamically modifies the priorities of each traffic

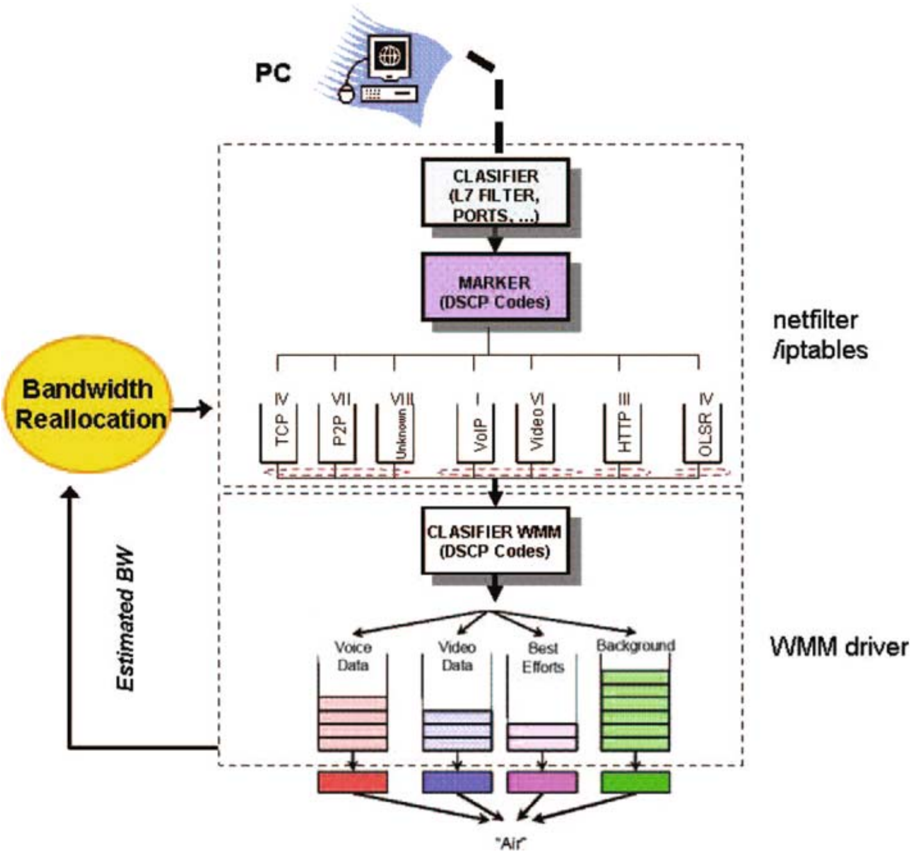


Fig. 12 Illustration of adaptive QoS strategy

WMM queue based on traffic availability information has been implemented, which permits improved QoS performance under more stringent bandwidth availability conditions.

6 Concluding Remarks

In the above sections, we have presented a pragmatic and cost-effective solution for providing broadband Internet access in rural and mountainous regions which is developed based on multi-hop wireless mesh networking technologies. While various challenges and solutions for designing such a wireless network exist, two main aspects in the designed WMN, namely routing enhancements and QoS features, are of functional importance and have been described in details in this paper.

The developed enhancements to the OLSR routing protocol increase network reliability, path stability, protocol efficiency and functionality of a multi-hop wireless mesh network thanks to advanced features such as metric-based routing, hierarchical topology, multi-homing with load balancing, cross-layer design, and multiple interfaces. At the same time, the proposed QoS mechanisms adopt a non-conventional approach which takes both delay sensitivity and bandwidth requirements into consideration for traffic classification, in order to ensure the best possible perceivable QoS for an essential set of services to all end-users while maximizing network resource utilization. Together with other designed and implemented mechanisms, the developed solution demonstrates a paradigm of using multi-hop mesh wireless networks for providing reliable broadband Internet access in rural and mountainous areas.

The designed techniques presented in this paper have been implemented, converted into binary image, and installed in Linux-based backbone nodes and mesh routers. An operational network which is installed based on the implemented codes has been given as an example of the real-life deployments. The experimental results demonstrate that the network functions according to the specifications imposed in the design. One practical lesson we learnt from the real-life networks is that link stability is of critical importance for the proper functioning of a WMN and that traditional hop-count based routing would not be able provide a stable path for the purpose of Internet access. In other words, traditional hop-count based routing must be enhanced to incorporate metric-based routing in order to provide stable and reliable path for end-users. Currently, more real-life deployments based on the presented solution in this paper are undergoing in Northern Italy and other rural and mountainous regions as well.

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