ADHOCSYS: Robust and Service-Oriented Wireless Mesh Networks to Bridge the Digital Divide

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Abstract—**While various wireless mesh networks are being deployed in urban areas and university campuses for diverse purposes, less effort has been devoted to use such networks for broadband access in rural and mountain areas. In this paper, we present a broadband Internet access paradigm using multi-hop wireless mesh networks which is currently being validated using a real-life pilot network deployed in a small village in Northern Italy. This solution is developed by the ADHOCSYS project, which is financed by the European Commission under the FP6 IST strategic objective "Broadband for All". Challenges exist in various aspects in order to develop a robust and service-oriented network, including for example network architecture, application scenarios, auto-configuration, routing, QoS, security and authentication, power supply, hardware selection and software development, business model etc. Following a general vision of the project, two key aspects, i. e. routing and QoS, are presented in more details in this paper.**

I. INTRODUCTION

In today's information society, more and more terminals, either wired or wireless, are getting connected to the global Internet. While access speed in urban areas is steadily increasing, the ability to provide various Quality of Service (QoS) demanding multimedia applications and broadband access is still not a reality in many rural and mountainous areas. Technological and social development for inhabitants in such areas is obstructed, since they cannot benefit from many essential Internet services. This gap has been lately defined as the "digital divide".

Wireless networks give the inhabitants in areas suffering from the digital divide a chance to be connected to the Internet by means of a wireless connection [5], provided that a wireless access point or base station is available in the proximity of the clients. Wireless Local Area Networks (WLANs), 3G cellular networks and WiMAX are among others a few candidate technologies for broadband access. However, these one-hop wireless networks either have limited coverage (e.g. WLANs) or are too costly (e.g. 3G and WiMAX) since they operate usually on licensed frequencies. One the other hand, multi-hop Wireless Mesh Networks (WMNs) [1] have recently emerged as an important networking technology, exhibiting reliable, flexible and extendable features. Although diverse application scenarios exist, using outdoor wireless mesh networks as a means for broadband Internet access in municipalities appears as a promising WMN application paradigm. However, successful deployments and operation of such networks depend heavily on various factors, such as underline networking technologies, applicability to specific environments, supported applications with user satisfaction, security measures, and business model.

In this paper, we present an example of such WMN deployment developed by the FP6 IST ADHOCSYS project, which aims at providing broadband access in rural and mountain areas where other wired or one-hop wireless connections are not available or non-profitable. Various aspects for designing an ADHOCSYS network have been carefully studied and solutions have been implemented, including self-organization, self-healing, routing, QoS, security and authentication, reliability analysis, outdoor power supply, real-life deployment, business model, software licensing etc.

Basically, ADHOCSYS networks are organized as a two-tier multi-hop wireless mesh network, operated in an ad hoc fashion, in order to provide high flexibility and scalability. The network provides end-users with access both to a minimum set of services such as e-mail and web browsing services and advanced services such as high bit rate multimedia contents and IP telephony. An extended version of the Optimized Link State Routing (OLSR) protocol [4] with new features developed in the context of the ADHOCSYS project has been used as the routing protocol. Through the deployment of ADHOCSYS networks, we demonstrate multi-hop wireless mesh networking as an emerging technology, paving the way to the future Internet evolution. In this paper, we focus solely on routing and QoS aspects of the ADHOCSYS networks, while the other aspects are only briefly mentioned in Section II.

The rest of this paper is organized as follows. Section II describes briefly the ADHOCYS project vision. Enhancements to the OLSR routing protocol are described in Section III while the QoS approach is presented in Section IV. Finally, concluding remarks are given in Section V.

II. THE ADHOCSYS VISION

The main use cases of mesh networks which are currently being deployed elsewhere are urban areas and/or university campuses [1]. Environmental conditions of such areas are quite different, and somewhat more user friendly, with respect to the usual conditions of areas suffering from digital divide, where, for instance, spatial node proximity and node accessibility cannot be taken for granted. Other issues to be addressed when considering a typical ADHOCSYS target scenario are extreme weather conditions, long distance links, large network sizes and investment budget availability [2] [3].

A. *Network architecture*

Figure 1 illustrates a typical case study for the ADHOCSYS network in a two-level hierarchy, in which the expected number of nodes could be high (from one hundred to one thousand or even more) and the area to be covered could be vast. The first tier backbone network is composed of multi-hop connections with several long distance wireless links, typically based on 802.11a links and directional antennas. The second tier access networks are mesh networks with short wireless links among a set of connected Access Points (APs), typically based on 802.11b/g links, serving as access points for end-users. The network is based on static topology, but exhibits also ad hoc characteristics. Nomadic nodes are supported by the network, but they do not participate in routing.

ADHOCSYS network nodes are divided into three categories, namely Type-1, Type-2 and Type-3 nodes, whose characteristics are shown in Table I. Type-1 and Type-2 nodes in ADHOCSYS have similar functions as Mesh Points and Mesh Access Points in 802.11s [6] networks. In addition to these three types of nodes, gateway nodes are also needed, in order to achieve Internet connectivity. The gateway nodes, which are installed at the edge(s) of towns and villages, must have at least two interfaces, one with connection to the Internet, and the other towards the wireless ADHOCSYS network. Furthermore, multiple gateway nodes are deployed so that the benefit of multi-homing, higher reliability, multiple routes, and load balancing can be achieved.

B. *Application scenarios and building blocks*

The primary application scenario defined in ADHOCSYS is targeted at providing broadband Internet access in rural and mountain areas through multi-homed wireless mesh networks.

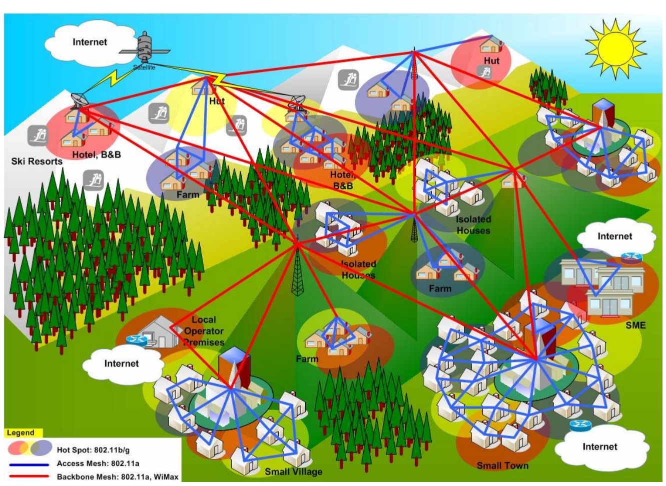

Figure 1. Typical ADHOCSYS network architecture.

TABLE I. TYPOLOGIES OF ADHOCSYS NODES.

Node type	Function	Internet gateway functionality?	Take part in routing?
Type-1	Backbone network	Yes	Yes
Type-2	Mesh access network	Yes	Yes
Type-3	Clients (end-users,visitors)	No	No

Discussions on other potential application scenarios can be found in [3]. As mentioned in Section I, various technologies and factors, regarding all aspects of ADHOCSYS networks have been considered in order to form the network building blocks, such as:

- Self-organization and self-healing features give the network the ability to be auto-configured and to recover automatically from node or link failures.
- Reliability analysis predicts the availability of the network in relation to the number of redundant network components needed.
- Security and authentication mechanisms protect network infrastructure and customers from possible attacks and ensure access only by authenticated and authorized users.
- Stand-alone power supply deals with situations when nodes (usually Type-1 nodes) are installed outdoor and must be battery powered.
- Real-life deployment, including site planning and how to convert implemented algorithms and mechanisms into a software image running on Linux boxes.
- Software licensing. The developed software has been released as open source code for free downloading at [7].
- Business model. Two types of business models have been proposed, applying to either mesh network operators (e.g. a local municipality who provides network infrastructure to its inhabitants) or end-users respectively.

III. ROUTING IN ADHOCSYS NETWORKS

A. *OLSR Enhancements*

In order to develop a routing protocol that fulfills the requirements [2] for building an ADHOCSYS network as described above, we have developed an extended version of OLSR [4] with the following enhancements.

- **Hierarchical structure.** Only two levels of hierarchy are defined: Level-1 corresponds to connection among backbone network nodes and Level-2 corresponds to connection among access network nodes. 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 pre-defined and are connected to each other. The cluster heads aggregate IP addresses in each cluster and are responsible for communications between clusters. Host and Node Association (HNA) messages are used for disseminating both the Internet gateway information and the connectivity information among different network clusters.

- **Multi-homing and load balancing.** With our 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 and other QoS parameters, in addition to the number of hops. 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 as a plug-in to OLSR. For multi-homed networks, the traffic load status is monitored at each gateway and is disseminated to other nodes inside the network, using a modified HNA message. Once this information is available at each router, the router could re-route its traffic towards a lighter-loaded gateway. This process needs to be carried out periodically so that the traffic load through the whole network is balanced among available gateways.

- **Multiple interfaces with metric-based routing.** With multiple interface extension, each interface is treated independently, so that higher path reliability and higher throughput can be achieved. With two interfaces between a pair of nodes, the link between these two nodes is still available even if one of the two channels is broken. Among multiple available paths between a specific pair of source and destination, the best path will be selected based on metric-based routing. In case of a link break or path failure, an alternative path can be obtained immediately for providing a reliable route.

- **Cross-layer design: link layer notification.** When a link break happens, traditional OLSR will react to this change by exchanging HELLO and Topology Control (TC) messages which 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, and upon receiving such an indication which is treated as a topology or neighbor change, OLSR shall conduct routing table re-calculation immediately.

- **Power aware routing.** Some nodes in ADHOCSYS networks may be installed in open environments without Alternating Current (AC) power supply. As an enhancement to OLSR, a power-aware plug-in which disseminates the battery level throughout the network, imposing routing table re-calculation when necessary, has been implemented. Additionally, an alarm message will be sent to the system administrator for possible human intervention when the battery level is lower than certain threshold.

B. Numerical results

As an example to illustrate the benefit introduced by our OLSR enhancements, we present in Figures 2 and 3 simulation results comparing OLSR and HOLSR. In Figure 2 the time needed for the standard OLSR protocol to achieve network stability, i.e. the convergence time when every node in the network has established route to every other node, is compared to the time needed by the proposed HOLSR protocol. With OLSR, stability time varies deeply depending on the number of nodes which take part in routing. On the other hand, in networks with different sizes, the HOLSR protocol keeps its performance more constant until it reaches stabilization. This is because that the stability within a cluster is achieved quite soon and at the same time cluster heads exchange instantly connectivity information among them (through HNA messages) about nodes that belong to their clusters.

Figure 3 illustrates the routing overhead (in terms of packets per second) as a function of the number of nodes which take part in routing. With less than 40 nodes, flat OLSR has a slightly smaller overhead of routing messages. From 40 nodes up over, the overhead in OLSR protocol grows substantially whereas in the hierarchical scenario, HOLSR protocol, it grows gradually. Taking into account these results, although the idea of using flat routing protocols could be considered in small networks (< 50 nodes more or less), using hierarchical routing will produce almost the same performance.

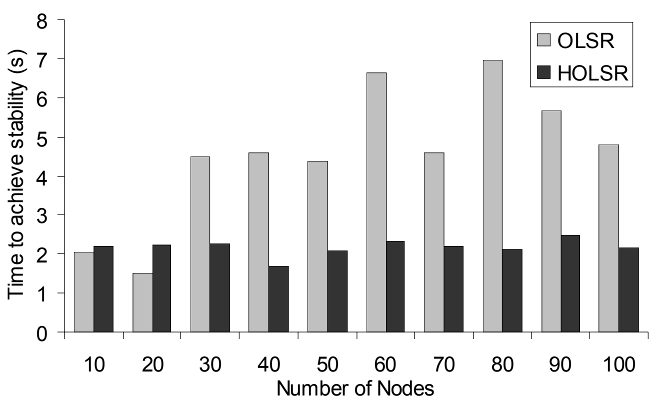

Figure 2. Time to achieve stability as a fuction of the number of nodes.

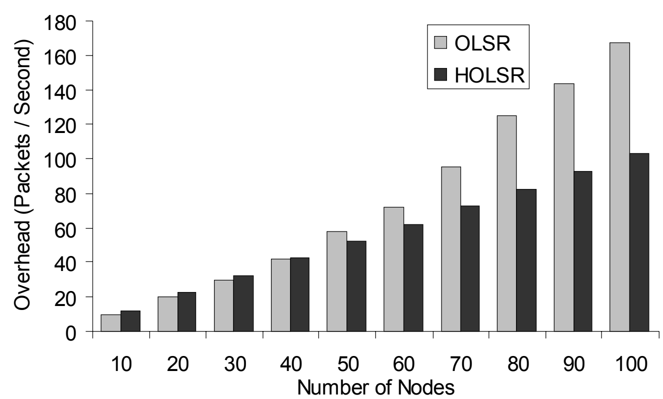

Figure 3. Routing overhead as a function of the number of nodes.

TABLE II. APPLICATION CLASSES CONSIDERED IN ADHOCSYS.

Class	Applications
I	Strong latency constraint, small bandwidth (VoIP, chat)
II	High throughput (transaction processing, file transfer)
III	Interactive, best-effort (web browsing, e-mail.) *Essential set of services for the users*
IV	Routing, battery information *Essential set of services for the network*
V	Emergency calls
VI	High throughput and latency constraint (streaming video)
VII	P2P applications
VIII	Unclassified traffic

However, when the network size is larger (> 50 nodes), the standard OLSR protocol expresses obvious scalability problems, whereas in the HOLSR protocol the overhead grows proportionally to the number of nodes. Moreover, the routing traffic is kept within each cluster thanks to the use of private address allocation and aggregation. In fact, using subnet-directed-broadcast addresses bounded by addresses with netmask, broadcast messages will be received and correctly interpreted only by nodes within the same cluster.

IV. QOS CONSIDERATION AND IMPLEMENTATION

The QoS mechanisms adopted in ADHOCSYS networks include traffic class priority definition, flow identification and classification, bandwidth measurement, Connection Admission Control (CAC), etc. In the following, we describe relevant information to a few aspects.

A. Background information on 802.11e and WMM

The IEEE 802.11e TG has standardized an enhanced MAC protocol, aiming at providing mechanisms for service differentiations and overcoming the intrinsic QoS problems in the 802.11 wireless networks. In the meantime, to prevent market fragmentation caused by non-interoperable devices based on the 802.11e standard draft, the Wi-Fi Alliance has also defined a specification for the implementation of a subset of the draft 802.11e standard supplement, the so-called Wireless Multimedia (WMM) [8]. A representation of the WMM mechanism is presented in Figure 4. WMM is supported by many wireless devices, and the MadWiFi drivers chosen for ADHOCSYS nodes fully support the WMM specifications as well.

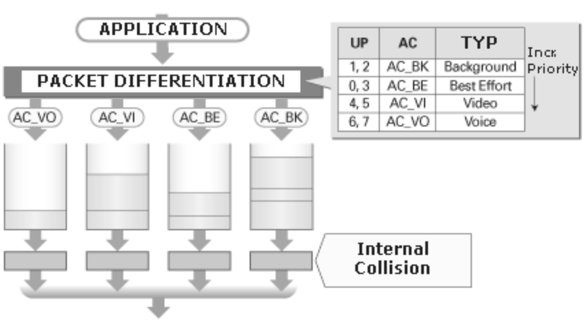

Figure 4. WMM: representation of a subset of the 802.11e MAC.

TABLE III. MAPPING BETWEEN APPLICATION CLASSES, APPLICATION CATEGORIES AND WMM ACCESS CATEGORIES.

Application Category	Application Class	WMM Access Category
C	II, VII, VIII	0 (Best Effort)
B	I, VI	1
A	III	2
A, B	IV, V	3 (Highest Priority)

B. QoS priority definition

Given the consideration that an ADHOCSYS network is designed to guarantee first of all a set of essential services like e-mail and web-browsing, the QoS priority classification has been defined in a non-conventional way, as presented below. High level services, such as video streaming, IP Telephony and emergency calls, are provided under specific conditions, depending on particular ADHOCSYS application scenarios. The traffic class definition and class mapping to WMM are illustrated in Table II and Table III respectively.

One major difference between the conventional QoS definition and ours is the different treatment of high bandwidth-demanding multimedia applications. While the conventional QoS vision puts Application Class VI in the second highest priority class of WMM, (AC_VI), we allocate this traffic typology to the best effort class (AC_BE). In other words, *while the conventional QoS class definition relies mainly on parameters such as delay sensitivity and bit error rate, we have further considered bandwidth requirement of an application, in addition to its delay sensitivity*. Moreover, our QoS definition is not node-based, but flow-based, which means that the traffic flows generated or received by a node may belong to different classes, as time varies. In more details, applications are classified based on their QoS requirements, as presented in Table II.

Application Classes I, II, III are defined based on the conventional QoS classification. Classes from IV to VII have been defined in order to allow finer service differentiation policies. It is also worth noting that our QoS class priority definition gives priority to traffic flows belonging to application Class III services, in normal conditions. When emergency calls occur, nevertheless, priority will be given to Class V traffic. The considered application classes have then been further categorized into three application categories, in order to exploit the Hierarchical Token Bucket (HTB) functionalities. Essential services for both users and networks are inserted in Category A. Category B groups flows with strict delay constraints, while Category C groups high throughput (but not essential) applications and uncategorized flows. Table III illustrates the mapping between Application Categories, Application Classes and WMM Access Categories (ACs).

C. QoS implementation in ADHOCSYS

As mentioned in Sec. IV.A, WMM-based hardware has been selected for building ADHOCSYS nodes. WMM offers high efficiency levels by means of channel utilization only when it is configured to work in a probabilistic way (soft QoS).

Although service differentiation via deterministic QoS (hard QoS) can still be obtained by using WMM only, it dramatically reduces the overall efficiency in channel utilization. On the other hand, hard QoS can still be provided by using the QoS features of the Linux Kernel. The OpenWRT distribution [9], installed in ADHOCSYS nodes, already provides the necessary application level (Linux) mechanisms. In particular, the HTB mechanism [10] manages the node outbound policy and is currently employed in many commercial products to guarantee for service differentiation in wired networks.

Due to these considerations, both HTB and WMM are used in our QoS implementation. Particularly, HTB has been employed in order to guarantee service differentiation within an ADHOCSYS node, while WMM will perform flow prioritization among different nodes. To guarantee interoperability between the HTB and WMM mechanisms a unique labeling of data packets is necessary. In ADHOCSYS, each information element (data packet) is classified via a unique IP Type of Service (TOS) value. No modification to physical and MAC layers is necessary, since the tagging is done at the IP layer (TOS field of the IPv4 header). When an ADHOCSYS node receives a packet, its source is checked. If an incoming packet comes from an external source (Internet gateway, users attached to the ADHOCSYS network), it is analyzed and classified (tagged) by our traffic classification module. Since the classification mechanism can be computationally intensive if it is run on all nodes, the classification is made only once at the borders of the ADHOCSYS core network (gateway, Access Points). Therefore, the likelihood that a non-classified (non-tagged) packet enters the network has been kept very low.

D. CAC

The overall goal for using Connection Admission Control (CAC) in ADHOCSYS is to keep the network working in non-saturated conditions in order to ensure QoS. More specifically, CAC in ADHOCSYS networks is done in a distributed manner, i.e. each type-2 node (AP) makes its decision relying on locally available information. Based on the measured available bandwidth, the AP is going to decide whether a request should be accepted or not.

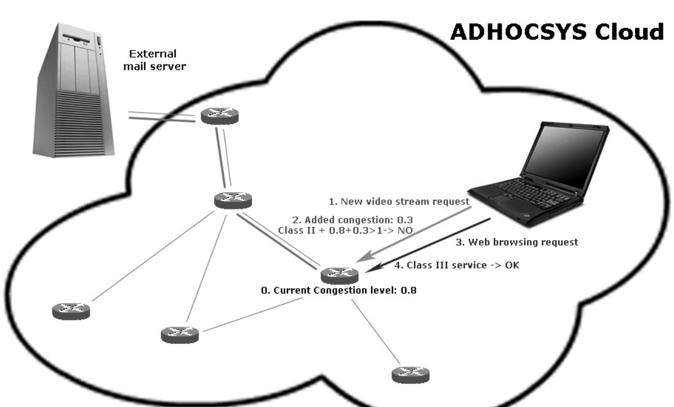

Figure 5. The CAC mechanism employed by ADHOCSYS.

However, the CAC procedure applies only to application types not belonging to the essential set of services. To keep the network not saturated, a combination of scheduling and buffer management is used together with CAC.

V. CONCLUSIONS AND FURTHER WORK

Wireless mesh networks are regarded as one of the most important networking technologies for ubiquitous Internet access and computing in the future. However, various challenges exist for successful deployments of WMNs, both technically and economically. In this paper we have presented a pragmatic and cost-effective paradigm to use multi-hop WMN to provide broadband access in rural and mountainous regions. The developed WMN provides a robust and service-oriented solution with sufficient reliability, flexibility, extendability and scalability of a multi-hop WMN, thanks to advanced features such as hierarchical topology, multi-homing with load balancing, cross-layer design, and multi-channel. 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 ADHOCSYS networks demonstrate a paradigm of using multi-hop meshed wireless networks for bridging the digital divide in rural and mountainous areas.

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