A Cost Effective Solution for Broadband Internet Access in Rural and Mountainous Regions

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Abstract

While bandwidth for Internet access in urban areas is steadily increasing in recent years, some rural areas are still suffering from digital divide. This paper presents a broadband Internet access solution developed by the ADHOCSYS project, which is financed by the European Commission under the FP6 IST strategic objective "Broadband for All". Aiming at providing reliable Internet access in rural and mountainous regions where xDSL is not available or non-profitable, the ADHOCSYS network provides a cost-effective solution based on multi-hop wireless networks. Starting from a general description of the network architecture and application scenarios, the paper presents various challenges and technical solutions which have been investigated within the project, including routing, QoS, power supply, and security. A real-life pilot ADHOCSYS network has been deployed in Northern Italy to validate the broadband access solution developed by the project.

I Introduction

Today, the Internet is far more robust and far more ubiquitous than it used to be five or ten 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). On the other hand, broadband Internet connections and ubiquitous access in many rural and mountainous areas are still not a reality, and for this reason these areas are still experiencing the digital divide in terms of the types of services that they can receive and how fast these services can be accessed.

To provide broadband access to residential costumers, various technologies, such as optic fiber, twisted pair cables, cable TV, Digital Subscriber Line (DSL), satellite communications, and wireless networks can be used. Although DSL appears as probably the most popular technology for broadband access in urban areas, it has its intrinsic limitation in rural and mountainous areas, due to its quite limited coverage. Wireless networks, and especially IEEE 802.11 Wireless Local Area Networks (WLANs), instead, exhibit obvious advantages over their wire-line counterparts however also with very limited coverage. Multi-hop wireless mesh networking, on the other hand, emerges as a promising technology in such context since it provides both wireless solution and wide coverage.

Although significant efforts on mesh network experimentations have been made [9], current deployments of mesh networks are mainly targeting urban areas and/or university campuses. These environments are more friendly to network deployments, maintenance and operations since, compared to rural counterparts, they are characterized by spatial node proximity, easier node accessibility, better weather conditions, shorter links, smaller network size and higher investment budget availability. Furthermore, the employed hardware, the deployed routing protocols, the installed software and the security strategies used in these networks do not support cost-effective operation of broadband services in rural and mountainous areas.

Aiming at providing broadband access specifically in rural and mountainous regions, ADHOCSYS networks are designed for providing broadband services in these areas, and provide end-users with access both to basic services such as e-mail and web browsing and 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, we have implemented an extended version of the Optimized Link State Routing (OLSR) protocol [4] with new features, and proposed a pragmatic approach for QoS provisioning in such networks. Other interesting aspects of ADHOCSYS networks include auto-configuration, self-healing, security and authentication, power supply, and reliability analysis. The implemented codes have been publicly released through the General Public License (GPL).

The rest of this paper is organized as follows. Section II gives a brief introduction to the ADHOCSYS networks, the architecture, typical scenarios and salient features. Section III describes our enhancements to the OLSR routing protocol. Section IV presents our QoS approach. Section V summarizes our reliability and availability approach, while the other aspects of the ADHOCSYS networks are summarized in Section VI. Sections VII and VIII deal with implementation, installation and testing activities. Finally, the concluding remarks are given in Section IX.

II. Network Architecture, Application Scenarios and Salient Features

A. Network architecture

An ADHOCSYS network might be large in terms of both geographic expansion and the number of nodes. Therefore a hierarchical architecture is needed to allow ADHOCSYS scale from few dozens to several hundreds nodes. A 2-tier hierarchy is a good tradeoff between network complexity and scalability. Refer to [1] [2] for more detailed descriptions on the network architecture.

The first tier backbone network is composed of multi-hop connections with several long distance wireless links. The backbone links are typically based on 802.11a, and long distances between transmitters and receivers are achieved through directional antennas. The second tier is composed by mesh networks with short wireless links connecting a set of nodes which serve as access points (APs) for end-users. The connections between APs and end-users are typically based on 802.11b/g links. The network topology is static but exhibits ad hoc characteristics, because nodes in the second tier could be switched on/off frequently.

Considering this architecture, ADHOCSYS network nodes can be divided into the following three categories:

- Type-1 nodes: wireless devices used for backbone networks. Type-1 nodes take part in routing.
- Type-2 nodes: wireless devices used for mesh access networks. Type-2 nodes take part in routing.
- Type-3 nodes: clients such as PCs, laptops, and PDAs, that are owned by end-users and do not take part in routing.

In addition to those three types of nodes, gateways nodes need also to be deployed in an ADHOCSYS network. A gateway node, which provides the connection between the Internet and the ADHOCSYS wireless network, can be configured from either a Type-1 node or a Type-2 node, by upgrading the node with an enhanced gateway functionality module (hardware and/or software). The gateway nodes must have at least two interfaces, with wired connection towards the fixed Internet and wireless connection towards the ADHOCSYS wireless network.

B. Application scenarios

The primary application scenario defined in ADHOCSYS is targeted at providing broadband Internet access to rural and mountainous areas through available gateway(s) installed at the edge(s) of towns and villages. Multiple gateway nodes are preferably installed, in order to achieve the benefit of multi-homing, higher reliability, and load balancing. Other application scenarios have also been envisaged, as discussed in [1] and [2]. This paper however focuses only on the primary scenario.

C. Salient features

Compared with other existing or upcoming multi-hop wireless networking technologies, for instance, the ones described in [5] and [6], the ADHOCSYS networks exhibit the following salient features.

- Multi-homing with load balancing. Through multi-homing, a more reliable network connection is provided 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 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.
- Multi-channel. This 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.
- QoS provisioning. QoS preference in ADHOCSYS network has been given to a set of essential services. This is different from conventional QoS definition that relies mainly on delay tolerance for traffic flow classification.
- Security and authentication. Mechanisms for security and authentication in both backbone and access networks have been implemented.
- Power awareness. The ADHOCSYS nodes in both backbone and access networks could be battery-powered, and power aware extensions to the OLSR routing protocol have been implemented.
- Open source codes. The implementation codes described in this article have been released as free software, already downloadable at [7], under the GPL.

III. Routing in ADHOCSYS Networks

In order to develop a routing protocol that fulfills the requirements [2] for building ADHOCSYS networks, we have made a number of enhancements to the OLSR protocol, as discussed below. More detailed descriptions of these enhancements and their implementation can be found in [8] and an accompany paper [10].

- Hierarchical structure. There are only two levels of hierarchy in ADHOCSYS networks. Level-1 hierarchy corresponds to connection among backbone network nodes, while Level-2 hierarchy 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. Figure 1 illustrates an example of such a network with two clusters. In addition to these two tiers, gateways to the Internet can be connected directly either to the first tier or to the second tier.
- Multi-homing. Host and Network Association (HNA) messages in OLSR allow gateway nodes to announce their network association (network address and netmask) with the Internet to other OLSR nodes.

With our multi-homing enhancement, the HNA messages have been modified to carry such information in the gateway advertisement so that 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.

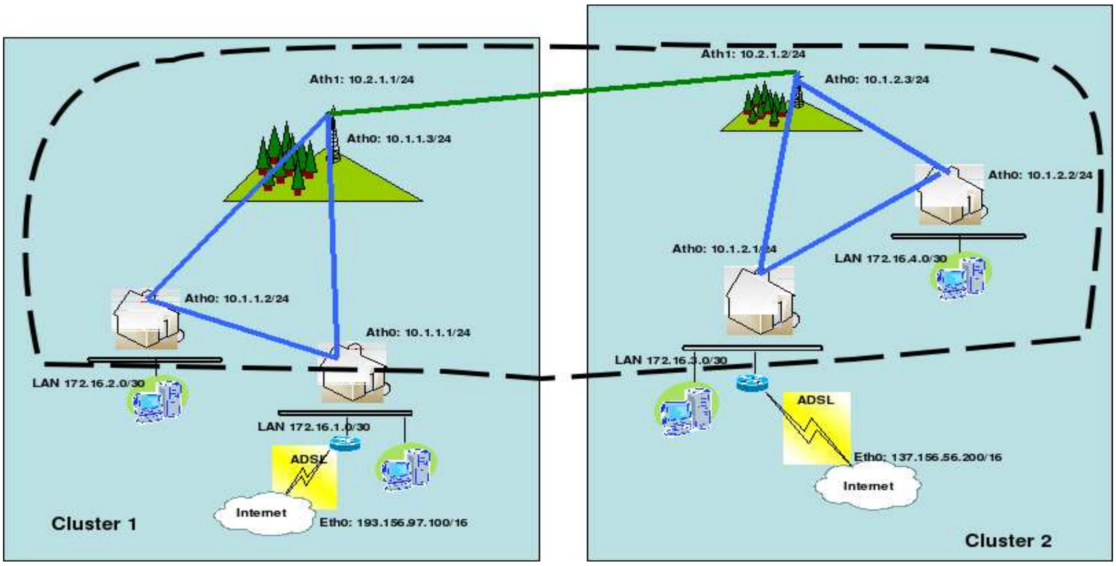

Figure 1 Hierarchical OLSR.

- Load balancing. Two types of load balancing have been considered in our network, namely load balancing among channels and paths. 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.
- Multiple interface support. The idea behind our multiple interface extension is to treat each interface independently, so that higher path reliability and higher throughput can be achieved when two or more interfaces co-exist between two routers. 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.
- Cross-layer design: link layer notification. 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.
- Routing table calculation. With our enhancement, a routing algorithm similar to the Dijkstra's algorithm has been implemented. 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 information needed for its routing calculation. This 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.
- Power aware routing. 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.

IV. QoS Approach in ADHOCSYS Networks

The ADHOCSYS project is aimed in first instance at providing to all end-users an essential set of services, which includes e-mail and web browsing. High level services, such as high quality video streaming, IP Telephony and emergency calls, can be provided under specific conditions, depending on particular ADHOCSYS application scenarios.

To implement such a QoS solution, we have defined a special traffic flow priority, as described in this section. Other QoS mechanisms in ADHOCSYS networks include flow identification, buffer management and queuing disciplines, traffic load measurement and Connection Admission Control (CAC). Both probabilistic (soft) QoS and deterministic QoS have been provided by using Wireless Multimedia (WMM) and Hierarchical Token Bucket (HTB) respectively. Refer to [8] for more detailed descriptions about these mechanisms and their implementations.

The following categorization has been defined and used for traffic classification in ADHOCSYS networks:

- 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: 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).

The above QoS definition for application Classes I, II, III is based on the conventional QoS classification which relies mainly on delay tolerance of different service classes. Classes from IV to VII have been defined in order to allow finer service differentiation policies.

To better exploit the functionalities of the HTB mechanism, these application classes have been further categorized into three application categories. 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 I shows the mapping between application categories, application classes and WMM Access Categories (ACs). The differentiation mechanism implemented in the HTB tree is also presented in the same table.

HTB Category	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)

Table I. Mapping between application classes, application categories and WMM access categories.

One major difference with our QoS class definition, compared with the conventional QoS definition, is related to the different treatment for high bandwidth-demanding multimedia applications. While the conventional QoS vision puts this kind of traffic in the second highest priority class, that is, AC 2 (corresponding to AC_VI class in the vision of 802.11e/WMM), we allocate this traffic typology to the best effort class (AC 1). 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 traffic class definition.

Note also that our QoS definition is not node-based, but flow-based, which means that the 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 application Class III services, in normal conditions. When emergency calls occur, nevertheless, priority will be given to Class V traffic.

V. Reliability and Availability Prediction

In order to achieve reliability in ADHOCSYS networks, several aspects which affect reliability have been considered in our study [1] [3]. These aspects are node reliability, power supply reliability, software reliability and link reliability.

In particular, node reliability may be affected by many factors, such as extreme weather conditions which lead to short circuits, drained batteries and power outages. Link reliability may also be affected by the instability of wireless channels itself.

To provide non-interrupted services to end-users, reliable routing mechanisms are required so that an end-to-end path is still available even if there is a link break along the routing path.

The ADHOCSYS reliability approach leans on the following steps:

1) Reliability Block Diagram (RBD) modeling: all the items involved in providing the network connection to a generic end user must be put into a graph in which series entities represent items necessary for the system to work and parallel entities represent redundancies.

2) Failure rates: Identify a failure rate for each building block in our system. These data can be obtained mainly from three sources, i.e. from the item manufacturer, relying on failure rate of similar equipment, or performing field evaluation using test-beds.

3) RBD reduction: A progressive simplification of the system level RBD applying some calculation derived from reliability theory. To help assuring a given availability level to the network services we are providing several scenarios with variable amount of redundancies.

The developed method can be used:

- to evaluate, in the network design phase, the best strategies to provide reliability through redundancy.
- to evaluate the achievable service availability versus the hardware and installation costs.
- to estimate the future maintenance costs.
- to assess the tradeoff to use fewer, more reliable, pieces of hardware versus a larger number of cheaper ones.

The main conclusion of this work is that to guarantee a 99.9% availability for basic services, it is necessary to reach most of the end-users with two redundant paths in two possible ways:

- both paths connecting the end-users to the Internet gateway with a small number of hops (3 or 4)
- to have one short path and a long one in a multi-homing configuration.

VI. Other Aspects in ADHOCSYS Networks

A. Channel selection

The channel selection problem in ADHOCSYS network is classified into three cases. That is, channel selection for 1) connections between backbone nodes; 2) connections between backbone nodes and access points; 3) connections between clients and access points. Since there are 3 and 11 non-overlapping channels for 802.11b/g and 802.11a respectively, the problem for channel selection in ADHOCSYS networks becomes how to select a channel which leads to least interference when both intra-system and inter-system interference is considered.

The proposed algorithm for this problem is a central-controlled solution where each node measures and reports the interference level in its neighborhood, and based on this information, a channel manager decides the most suitable channel for each pair of nodes.

B. Power supply

In rural and mountainous areas, some nodes of an ADHOCSYS network may be installed outdoors where no AC power is available. This means that battery power with renewable power source is mandatory in this case. To provide necessary power supply under various different operational conditions, techniques for designing stand-alone photovoltaic (PV) systems have been investigated and an operational stand-alone PV system has been developed. Additionally, techniques for reducing power consumption and increasing energy efficiency of the overall system have been developed, and a power-aware plug-in to the OLSR protocol has been implemented, in order to add another metric for best route selection based on the battery level of each node and to send alert messages when necessary [8].

C. Security and authentication

According to the roles of the nodes in ADHOCSYS networks, security issues have been classified in two different categories: Category 1, user-oriented, targeted for Type-3 nodes; and Category 2, infrastructure-oriented, targeted for Type-1 and Type-2 nodes. Category 1 includes security mechanisms for users who do not participate in routing process, while Category 2 deals with problems related to backbone nodes which form the infrastructure and are active routing nodes in the network.

For Category 1, the main requirement is to grant access only to authenticated end-users. In order to accomplish this task two mechanisms are used, namely Captive Portal to grant web based authentication access and IEEE 801.1x to grant port based authentication access.

For the Category 2 the following solutions can be adopted: interface virtualization which supports multiple-purpose antennas, secure routing in order to authenticate routing messages signing advertisements and data protection to secure network traffic using encryption.

D. Initial auto-configuration and IP address allocation

Another important aspect of ADHOCSYS networks is initial auto-configuration and IP address assignment to routers and end-users. Private addresses with Network Address Translation (NAT) have been used in our design. More specifically, 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/or monitored by a central controller co-located together with the system administration office.

VII. Implementation and Installation

All mechanisms and algorithms described in the above sections have been implemented, and the implemented functionalities have been tested on small scale Linux-based test-beds and via ns2 simulation.

For example, ns2 simulation has been used to test our implementation of hierarchical OLSR, since this feature requires a large network to be demonstrated. As illustrated in Figure 2, the benefit of using HOLSR (with two clusters) appears when the node population exceeds 40 in such a network.

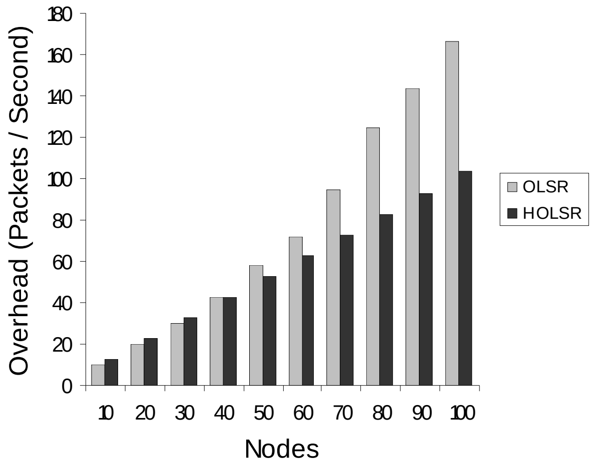

Figure 2 Hierarchical OLSR overhead

Another advantage of using HOLSR at these sizes is that the route convergence time becomes much shorter when HOLSR is employed.

To evaluate the applicability of our developed solution, an ADHOCSYS pilot network has been deployed in a mountain region located in Northern Italy (see [10] for more details). The deployed ADHOCSYS pilot network provides broadband Internet connection to inhabitants in a village which is located about 10 Kms from an Internet gateway. Any end-user covered by an AP can connect his/her PC or home network to a node Ethernet port to have broadband access to the Internet.

The access network consists of 10 Type-2 nodes, covering the whole village, and is connected through multi-hop Type-1 backbone nodes to the Internet Gateway. The nodes are based on the hardware platform selected in the ADHOCSYS project, and run the Linux operating system, with enhanced OLSR and other implementations developed in this project.

A few dozens of end-users act as Type-3 nodes and take part in the experimentation, which includes performance evaluation of implemented algorithms.

VIII. Testing Activities

The testing activities in the pilot network are being performed at the time of writing. Earlier testing activities, however, have been performed in order to verify the correct behavior of ADHOCSYS nodes, on smaller test-beds.

The following figure shows the configuration of one of the small test-beds that have been deployed in recent months. This network is composed by four nodes. Three nodes are ordinary PCs. Two of them are also connected to an Ethernet LAN, and one serves also as a gateway towards the Internet. Two PCs and the RouterBoard-based ADHOCSYS node are equipped with wireless cards. One PC and the ADHOCSYS node, in particular, have two wireless cards.

The RouterBoard-based ADHOCSYS node contains the ADHOCSYS enhanced version of the OLSR routing protocol, and all other software modules developed in this project. The following OLSR plug-ins have been activated and tested:

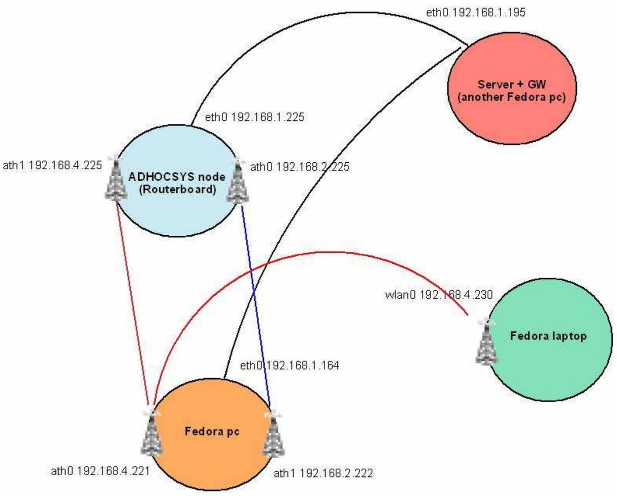

Figure 3 Architecture of one small test bed.

- POWERINFO: alert mechanism for nodes with nearly drained batteries
- MULTIFACE: enhancement for the support of multiple wireless interfaces
- LINKINFO: used to diffuse information about the current status of links
- CHANNELSET: to gather information about the channels currently in use
- ERC: routing table calculation

In this test-bed, we have performed some tests to verify the correct behavior of these plug-ins. Further test activities are currently being performed based on the real-life pilot network.

IX. Conclusions and Further Work

In this paper, we have presented a pragmatic and cost-effective solution for providing broadband Internet access in rural and mountainous regions through multi-hop wireless networks. Various aspects for designing such a wireless network have been presented, in particular main design challenges such as routing enhancements and QoS features, have been described in more details.

The developed enhancements to the OLSR routing protocol increase efficiency and functionality of a multi-hop wireless network thanks to advanced features such as hierarchical topology, multi-homing with load balancing, cross-layer design, and multi-path. 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 providing reliable broadband Internet access in rural and mountainous areas.

Currently, a pilot real-life network based on the above presented techniques has been deployed in Northern Italy. We foresee more deployments of such networks in other regions in the near future.

Acknowledgments

We would like to acknowledge the European Commission for their support. Our acknowledgement goes also to all ADHOCSYS partners for their co-operation and contribution in this project.

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