Mobile Ad-hoc Networks for Large In-Building Environments

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Abstract

Lately, wireless networks have gained acceptance for home networking. Low cost installation, flexibility and no fixed infrastructures have made it possible for in-building networks to rapidly adopt this technology. In this paper we introduce the use of mobile ad-hoc networks (MANETs) for large in-home environments, such as hospitals, government buildings, office and industrial buildings, etc. Thus, we adapt their protocols and algorithms, relaxing some restrictions that are inherited from traditional ad-hoc networks scenarios (battlefield, catastrophic disaster, etc) to better fit the specific characteristics of this new application field. In particular, we propose a routing algorithm oriented to improve the performance of MANETs for in-home networking.

1. Introduction

Traditionally, in-building networks have fixed infrastructures, either wired or access point –based when wireless. This makes it quite difficult to adapt the building to the new requirements of a specific new technology or service. Taking into account that the building lifetime is much longer than the one of that new technology, we can derive that, in general, current buildings are poorly designed for the future. For this reason users need new technologies that are faster and easier to deploy, configure and expand. Furthermore, new applications (collaborative work, e-learning, preventive health care etc.) and paradigms (ubiquitous computing, ambient intelligence, etc.) need some rethinking about how we design and integrate technology into our daily environments.

On the other hand, inside future buildings there will be a lot of heterogeneous devices from different manufacturers. From a practical point of view, the design of a common infrastructure is difficult because user requirements and application scenarios are very different and dynamic. Therefore it is important to have a flexible technology that allows the integration and expansion of existent infrastructures. Wireless networking is the most attractive approach for in-building environments, since it avoids the cost of pulling new wires and the challenges of using existing wiring 7.

Furthermore, recent advances in wireless technologies (Bluetooth 7, 802.11 7, ZigBee 7, etc.), under the mobile ad-hoc philosophy, have made it possible to establish wireless infrastructures that can be utilized not only as temporal networks but like a permanent building infrastructure.

Wireless ad-hoc networks are made up of hosts that communicate with each other over a wireless channel. The nodes have the ability to connect each other out of their ranges because intermediate nodes perform routing tasks.

Mobile ad-hoc networks (MANETs) have a set of characteristics that are interesting for in-home applications and environments:

- They do not need any fixed infrastructure support.
- The nodes are automatically configured (place and play philosophy).
- They can be fault tolerant.
- They offer support to mobile devices.

However, general MANET mechanisms assume the worst working conditions for each node in terms of power, bandwidth, mobility and so on (these restrictions come from the traditional MANET scenarios such a catastrophic disasters or battlefields). These conditions, with a very high impact in the quality of the communications, impose hard restrictions that limit the capabilities of the different nodes.

But in real networks, the worst conditions do not have to apply equally to all the nodes. Since the different nodes have in general different capabilities, we can take advantage of this situation to improve the performance of MANET protocols and algorithms.

In this paper we propose an architecture that uses mobile ad-hoc networks in large-scale building environments. This architecture will use a suitable model for the home networking problem to minimize the drawbacks of general MANET mechanisms, offering at the same time some desired features for the considered in-home applications and improving one of the main bottlenecks in MANETs performance, the routing algorithm.

The architecture described in this paper is based on a previous work called SENDA 7 (standing for *Services and Networks for Domotic Applications*) devoted to easily integrate networks, protocols and devices for home applications. SENDA middleware defines a set of simple device interfaces, a hierarchical composition mechanism for both device objects and event propagation, a set of interfaces for managing and initializing the network and a set of conventions for easier development of services.

In SENDA, some key factors were identified regarding the deployment of networks (data, control and multimedia) in in-building environments. These factors are flexibility, low cost installation and minimum configuration requirements. All these factors are present in current mobile ad-hoc networks.

On the other hand, some of the constraints assumed in general ad-hoc networks are no longer present in large in-building environments. We study these environments and identify which of their features ad-hoc mechanisms will benefit from.

The rest of this paper is organized as follows. Section 2 explains some previous work in home area networks. In section 3 the problem we try to tackle is characterized. Section 4 is devoted to the routing algorithm. In section 5 the prototype we have used to validate this architecture is briefly described. Finally we draw some conclusions and outline some future work.

2. Previous work

Wireless networking is perhaps the most attractive approach for the home, since it avoids the cost of pulling new wires and the challenges of using existing wiring7. Similar affirmation can be done for large in-home environments.

Traditional wireless infrastructures in buildings are based on the use of access points. With this approach, an important issue we should consider is the low fault tolerance of the resulting network. A failure in the base station makes all nodes within its coverage area not to be able to establish network connections. This problem is overcome in a MANET-based infrastructure because its nodes have the capability of finding alternative routes to connect each other. Another problem is the necessity to provide a wired infrastructure in all the places in which we need to set up an access point. This increases the costs and it is not a flexible solution at all.

So far, research in MANETs is mainly focused in the networking aspects. Although ad-hoc networking has been proposed as a promising approach for in-building infrastructures (i.e. ad-hoc networking communities7 or networked sensor systems7) the research community has not faced yet how the characteristics of these new environments can affect the ad-hoc mechanisms (QoS, routing…) and, in general, how to adapt them to in-home applications. However, recent works show the need of studying real world scenarios 7 and their influence in the performance of MANET mechanisms.

The idea of establishing a backbone network in order to improve the performance of the routing algorithm has been used in several works. Energy-conserving routing 7 and hierarchy-based routing protocols 7 are some examples. But usually, the proposed routing algorithms take into consideration neither the properties of the nodes that make up the network nor the specific characteristics of the environment.

On the other hand, previous works in the area of home services (OSGI7, HAVi7, HOME API7 etc.) try to integrate a lot of heterogeneous technologies without considering how these technologies will be deployed and how the interaction among technologies can be improved. These aspects are partially tackled in 7. In this work a method to extend the coverage of Bluetooth networks for the home is proposed. A similar approach is done in 7 with the UWB (ultra wideband) technology. But the possibility of sharing and integrating resources in a general infrastructure is still underway. Thus, the independent networks that coexist within a building (for instance, data, multimedia and control) are still underused due to their isolation from each other (i.e. a user cannot have access to a HAVi video streaming from a PDA).

3. Problem characterization

In current buildings we find more and more a lot of devices with wireless capabilities that have different characteristics in terms of mobility, performance and so forth.

Figure 1 depicts a typical scenario where, taking into account the above considerations, three types of ad-hoc nodes can be identified:

- *Vertebral nodes*: These are nodes with few position changes, with enough capabilities to perform management tasks and with no power consumption problems (desktop computers, information points, cash dispensers, some types of electrical appliances etc.). These nodes are represented with a black circle in Figure 1.
- *Auxiliary nodes*: We are referring to mobile nodes with still enough performance to do management tasks (laptop computers, etc.). These nodes are represented with a dark gray circle in Figure 1.
- *Clumsy nodes*: These nodes are characterized by their high mobility, their lower performance and their hard power restrictions (mobile phones, PDA ´s, etc.). These nodes are represented with a light gray circle in figure 1.

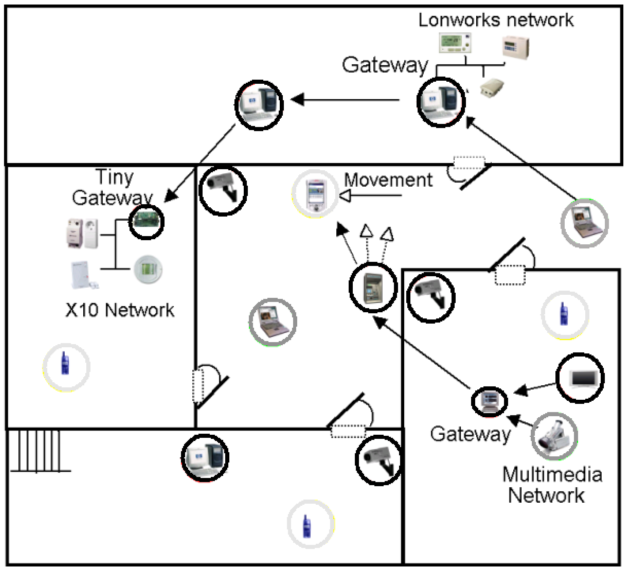

Figure 1 - Typical in-home environment with node classification

Clumsy nodes are sinks and sources of information and rarely need to do management tasks (only when, due to the existence of some faulty nodes, it is strictly necessary to establish new connections to keep the network working).
According to this classification, it is clear that management responsibilities will be assigned first to *vertebral* nodes, then to *auxiliary* nodes and finally, if needed, to *clumsy* nodes. In this paper we will consider only routing tasks, but the same philosophy would have to be followed with others, like service discovery, fault tolerance and so on.
A restriction imposed by our architecture is the necessity of establishing a set of nodes (*vertebral* nodes mainly), which provides a minimum coverage. This restriction is similar to the current problem with access point -based infrastructures. Nevertheless, in our architecture any of the nodes (generally *vertebral* and *auxiliary* nodes) can play this role and in the case of failure they can establish alternative paths through the other nodes (*vertebral*, *auxiliary* or even *clumsy* nodes).
Other elements that are present in the architecture are *gateways* or *bridges*, which are nodes that offer interconnection capabilities between devices from different technologies. We can use gateways from third parties; for example, an IEEE 1394 [9] to wireless 802.11 bridge has been developed by Philips [5]. With these types of bridges and with the interfaces defined in SENDA, we can control HAVi devices (multimedia platform based on an IEEE 1394 network 7) with, for example, a simple PDA with an 802.11 interface.

4. The Routing Algorithm

So as to consider the MANET –based model for large in-home environments described before, the routing algorithm must be able to take into account the different types of nodes that are present in the model as well as the specific characteristics of each node at every time. We have taken as starting point of our proposal the *Ad-hoc On-Demand Distance Vector* (AODV) algorithm 7.
Our approach takes the idea of the path establishment mechanism introduced by AODV, but improves it by avoiding, in the search for a route, nodes either with high mobility factor (mainly clumsy nodes) or very congested. Since routing tasks must be concentrated on the more capable nodes (vertebral and auxiliary nodes), we have designed a cost function that takes into account the different characteristics of the nodes. Thus, each node has a *routing quality* (RQ) factor as a function of its mobility and its congestion. Routes are selected according to the total RQ factor (sum of the individual RQ factors of the nodes that make up the route) and, of course, the number of these nodes (as the original AODV algorithm does).
The routing quality factor is dynamically adapted as a function of the amount of traffic forwarded by a node. In order to exclude congested nodes from new routes, nodes which have a lower routing quality factor are chosen first.
The function used to obtain the routing quality factor of given node t is (see Figure 3):

$$RQ(n) = e^{x(n)\alpha} + e^{y(n)\alpha}$$

where *x(n)* and *y(n)* represents, respectively, the mobility factor and the congestion of node *n*. The α factor allows us to react more or less quickly to changes in congestion and mobility factors.

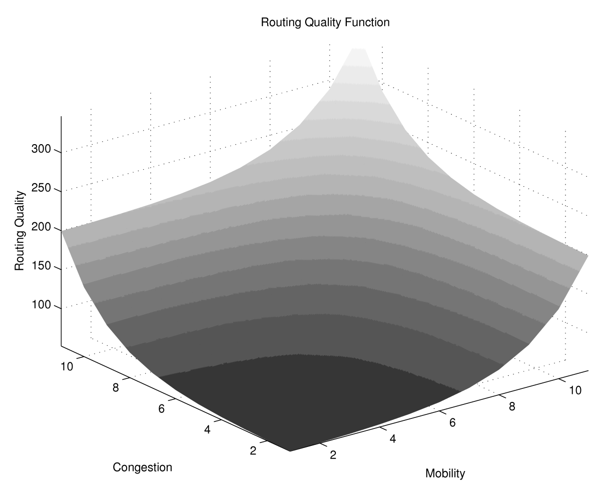

Figure 3 - Routing Quality function

Since RQ functions depend on exponential terms, any slight changes on $x(n)$ and $y(n)$ will produce significant variations. Thus, even an only node may be decisive to determine the best route.

The cost of a route in AODV is just the number of nodes in the route. In our proposal the total cost is complemented with the sum of the RQ factors of all the nodes that belong to the route. Since the cost of a route is evaluated at the beginning of the establishment phase, it does not depend on the variation of RQ with time. Consequently, our cost function, which should be minimized, is:

$$C = \beta N + (1-\beta)\sum_{k=1}^{N} RQ_t^{\,k}$$

where N is the number of nodes involved in the path and $RQ^K{}_t$ is the routing quality factor for node k in the route at time *t*. The β factor allows us to control the relative weight of the terms in the function. So, for β=1 we get routes only based on the number of nodes (the AODV algorithm). However, for β=0 we get routes only based on their accumulative RQ factors. These two components (N and RQ) must be balanced since with β=1 the algorithm introduces nodes in the route which are no really appropriate (high mobility, low performance, hard power constraints…) and with β=0 the algorithm establishes longer routes. Experimental results show that excessive long routes present high delay and high probability of link failure.

This cost function has two main advantages. First, the traffic is concentrated on nodes which have more stable positions (vertebral and auxiliary nodes) so we obtain more reliable communication paths. However, if we only consider the mobility factor, our vertebral nodes could be collapsed by traffic. This is the reason to include the congestion factor (*y(n)*). The second advantage comes right from the fact of using this congestion factor that creates a dynamic load balancing mechanism.

In order to include the RQ information in route discovery we also have modified the original AODV route discovery mechanism. When an intermediate node between source and destination receives a route request (RREQ) message, the node:

- Sends a request reply (RREP) message, if it has an unexpired entry for the destination in its route table. We assume that this route is the most appropriate route to destination (lowest weight).
- Sends a RREP, if it knows a more recent path or a path with lower RQ factor than the one previously known to sender.
- Increments both the value of the RQ factor (adding its own RQ factor to the total) and the RREQ count (number of intermediate nodes), and then broadcasts the RREQ request to its neighbors. In the case the obtained RQ factor is smaller than a previously forwarded RREQ, the new RREQ is also forwarded.

For the same route search, an intermediate node can receive several RREQs (identified by the source IP address and a unique ID) coming from different paths. The AODV algorithm just considers the first request (it is supposed to be the one with fewer nodes in the route) discarding the rest (it does not forward any of them in any case). In our approach, we must consider that the new RREQ may have a lower cost than the previously forwarded RREQ. In this case, the new RREQ is forwarded since it can lead to a more stable route.

Something similar happens with the destination node. For a unique route request, the intended destination can receive different RREQ with different costs (different RQ factors and number of nodes). In this case, the destination replies a RREP only if the value of C (cost) is less than the previous RREQ received. So the source starts the data packet transmission with the first RREP received but if it receives a new route with a better value of C, it has to update the route path with the new configuration.

With this modification we obtain a “quasi-backbone” network mainly composed of vertebral and auxiliary nodes. The connections are more stable because the probability of route failure is less since these nodes have low mobility and better performance (less chances of congestion). We should note that the probability of route failure is one of the main reasons for poor performance in large networks with source routing protocols (i.e. AODV) 7.

4.1 Simulation Results

In order to compare the variations in performance between our proposal and the AODV algorithm, we have run some simulations with the ns2 simulator 7.

The simulated environment is a square of 650x650 meters with 19 *vertebral* nodes, 30 *auxiliary* nodes and 11 *clumsy* nodes. The range of the nodes is 170 meters (the standard configuration of a node having a 2.4 GMHz Lucent Orinnoco Wavelant DSSS radio interface at 11Mbs), following a random movement (Random Waypoint model 7) and with the *environment mobility factor* described in 7. The total number of different scenarios is 76.

Overall, the percentage of forwarded packets (average) is shown in Table 1.

	AODV	***Routing Quality based***
Vertebral nodes	44,08 %	62,89 %
Auxiliary nodes	41,94 %	32,13 %
Clumsy nodes	13,98 %	4,98 %

Table 1 - Packets forwarded by every type of node

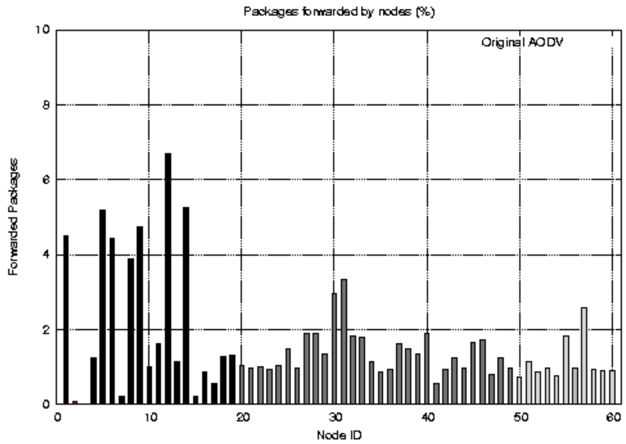

Figure 4 - Traffic forwarded by nodes using the original AODV algorithm.

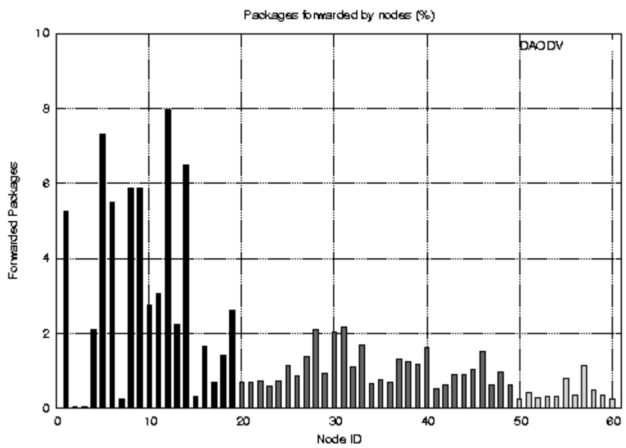

Figure 5 - Traffic forwarded by nodes using a quality routing based function

Detailed results per node are shown in Figures 4 and 5. The X-axis shows the node ID in the ns2 simulator. We can see how auxiliary and clumsy node (dark gray bars and light gray bars) forward less packets with our algorithm (figure 5), which moves the traffic to vertebral nodes (black bars).

From the scalability point of view, one of the problems we have to face next in how the network composition (in terms of the ratio between every type of node) impacts in the network performance. As we have already mentioned, although the RQ factor tries to avoid the inclusion of congested nodes in new routes, when the number of vertebral nodes is much less than the number of mobile nodes (*auxiliary* and mainly *clumsy* nodes), vertebral nodes can get congested creating an important bottleneck.

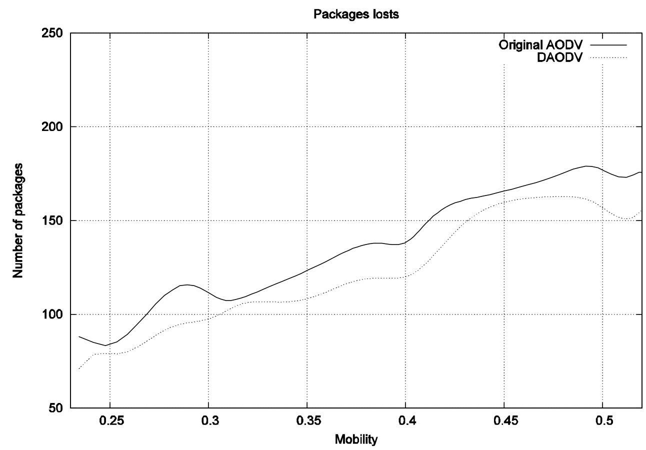

Figure 6 - Lost packets with AODV and our algorithm (DAODV).

Finally, Figure 6 shows the lost packets with the AODV algorithm and with our proposal. The X-axis shows all the different scenarios that have been simulates ordered according to the *environment mobility coefficient* defined in 7. We can see how the average loss obtained using the RQ factor based algorithm (dots line) is lower. As we mentioned before, this is because the connections are in this case more stable since they have been made through *vertebral* and *auxiliary* nodes (with low mobility factors).

5. Prototype

As we mentioned before, the proposed architecture is based on a previous work called SENDA. SENDA was initially designed having in mind the main problems that arise when you want to facilitate the deployment of services at home: the integration of networks, protocols and devices and the design and management of the services themselves. In this sense, the SENDA middleware is the key part of the architecture. Actually, SENDA's middleware implementation is CORBA 7 based.

Afterward, the use of mobile ad-hoc networks as the basic infrastructure for in-building networks, based on the capabilities described along this paper, came up as one of the most important goals. Thus, the SENDA prototype was extended to include the MANET approach described in this paper.

Two wireless ad-hoc gateways for the two most relevant home technologies (X10 and Lonworks) have been developed:

An X10 to 802.11 gateway implemented in a TINI (Dallas Semiconductor) device [10]. In order to allow us to perform the routing tasks, a Java version of the AODV algorithm has been developed.

The *Domobox@* gateway (developed in collaboration with Telefónica, the Spanish telephone company) 7. This device is a low cost interface to X10 and Lonworks technologies easily controlled through the TV remote control. Besides the Ethernet and the GPRS (General Packet Radio System) 7 interfaces, an 802.11 version was developed so as to make of it a vertebral node in our prototype.

The vertebral nodes are desktop computers with 802.11b extensions running GNU/Linux. Auxiliary nodes are laptops and *clumsy* nodes are PDAs and wireless devices with a PIC processor 7 used to control simple home appliances connected to the SENDA prototype.

6. Conclusion

Currently, in-building applications use a wide variety of technologies. User requirements include the need of using heterogeneous devices with different functionalities and low deployment and maintenance costs. Mobile ad-hoc networks offer a good solution to these problems as they fulfill all of these requirements.

In this paper, we have characterized the in-building scenarios so as to be able to successfully apply mobile ad-hoc networks mechanisms to large in-building environments. According to the proposed model, we have introduced a routing algorithm that takes advantage of the specific features of those environments to improve the performance of the MANET –based solution.

Finally, we have presented the prototype (based on a previous work called SENDA), where these proposals have been proved.

In the near future, our work is mainly focused on widening the range of services we can provide based on the SENDA architecture and using the MANET philosophy. In this sense, other issues related to in-home services and their applications in this scenario (SENDA and MANETs) should be studied (for instance, QoS arquitecture, service discovery, fault tolerance, security and so on).

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