Intelligent Routing Scheme in Home Networks

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Abstract Apart from ethernet, both wired and wireless technologies involved in home networking are prone to bandwidth fluctuations mostly due to interferences with others home devices or appliances. Channels characteristics are time variant and environment sensitive. Mobility and end devices density in a wireless cell may collapse available network resources. Therefore, quality of service provision for delay sensitive multimedia applications in such an unstable and dynamic network environment is important since there is no way to ensure that a reserved resource will maintain the required level of service over time. This paper presents an intelligent routing scheme based on the multi-agent system technology. Agents are embedded in nodes and cooperate to build alternatives routes. These routes are used as backup routes when those defined by the routing protocol become inadequate.

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Introduction

Not so long ago, most homes used a single PC to access the Internet and share files. Nowadays, the situation is different. A myriad of disparate electronics ecosystems populate the average household, including:

- PC centric ecosystems composed of modems, scanners, digital cameras, and printers connected to a localized network
- Multimedia ecosystems consisting of set-top boxes, digital TV, digital video recorders, stereos, and DVD players
- Wireless centric ecosystems that comprise personal digital assistants (PDAs) and mobile phone sets

The home networking challenge is to enable a transparent communication among these ecosystems and also home devices connection to the broadband Internet. Indeed, customers want their devices to work together everywhere and at any time. With the emergence of advanced networking technologies such as PLC (Power Line Communication), MoCA (Multimedia over Cable Alliance), HomePNA (Home Phoneline Networking Alliance) and various wireless communication technologies, home networking has become a reality. However, these home dominant networking technologies suffer from several shortcomings. Their channels characteristics are environment sensitive and often fluctuate over time. The provided bandwidth can collapse rapidly if any interference occurs. For instance, a washing machine turning on can degrade considerably the power line network performance and affect the overall quality of service. Since such a situation is unpredictable, the use of a bandwidth reservation mechanism to ensure QoS to multimedia applications does not guaranty network resources availability over time. A resilient mechanism is required to ensure route maintenance during a multimedia content delivery.

In this paper, a distributed knowledge plane over a mesh home network architecture is proposed. Based on a lightweight multi-agent system, it enables an efficient piloting of the routing process. The knowledge plane is built in overlay of the routing protocol and contains a set of alternatives relevant routes to nodes' routing table destinations. These routes are activated each time a problem occurs.

The paper is organized as follows. Section 1 introduces our home network architecture. Section 2 describes the distributed knowledge plane that enables intelligent routing. Then, sections 3 and 4 respectively provide a testbed environment presentation and some simulated cases. Finally, results are analyzed in section 5 and future works are outlined in section 6.

1 Home Network Architecture

The main purpose of the home network is to allow users to connect various devices such as desktop computers, laptops, games consoles, and cameras to the Internet and to each other. For instance, end users must be able to watch a movie stored on digital video recorder (DVR) located in the living room on a TV located in the bedroom. Until now, there is no common accepted architecture for home networks. Two organizations with different approaches are working actively on the home networking definition.

The first regroups telcos in the HGI (Home Gateway Initiative) consortium. The HGI approach consists of building home networks around a single device: the home gateway which acts as a central point for distributing both LAN-initiated and WAN-initiated services [1]. The second, DLNA (Digital Living Network Alliance), is composed of consumer's electronics manufacturers and proposes a device centric home network architecture where each device can communicate directly with others through wired or wireless connectivity [2].

Both network set-ups have some weaknesses. The HGI architecture provides a better management of communications and facilitates the provision of QoS since the home gateway has a global vision of the network. However, the whole network depends on the gateway operation. This approach is not fault-tolerant. DLNA prone a fully distributed network architecture (scalability, availability, robustness) but does not define how the network should be implemented.

1.1 Home network basic requirements

A home network must satisfy the following requirements:

- **The whole house coverage**: home devices should be connected everywhere and at all times. That is why the network must cover the whole house.
- **Resiliency**: the home network is not at the shelter of breakdowns. The network architecture must ensure as much as possible that a link breakdown or a device outage will not affect the global network availability.
- **No new wire installation**: the deployment of a home network must not require a large scale installation of new wiring in the home.
- **Efficient use of technologies' diversity**: the home network architecture should ensure that applications take advantage of the networking technologies diversity for the QoS provision.

1.2 The proposed architecture

To achieve these requirements, we propose to build the home network around a set of dedicated devices.(figure 1). These devices form the network core and are connected to each other at least with one the networking technologies. They act as access points for end devices. The network is thus composed of:

- **mesh access point routers** (MAPs) disseminated in the house so that each home device has at least one network access. A MAP has multiple interfaces, one for each networking technology. It combines routing and bridging functions. MAPs form an hybrid mesh network.

- **end devices** that can access the network with a wireless technology through a MAP or directly with PLC or MoCA technology. However, mobile end devices do not have a wired connection.

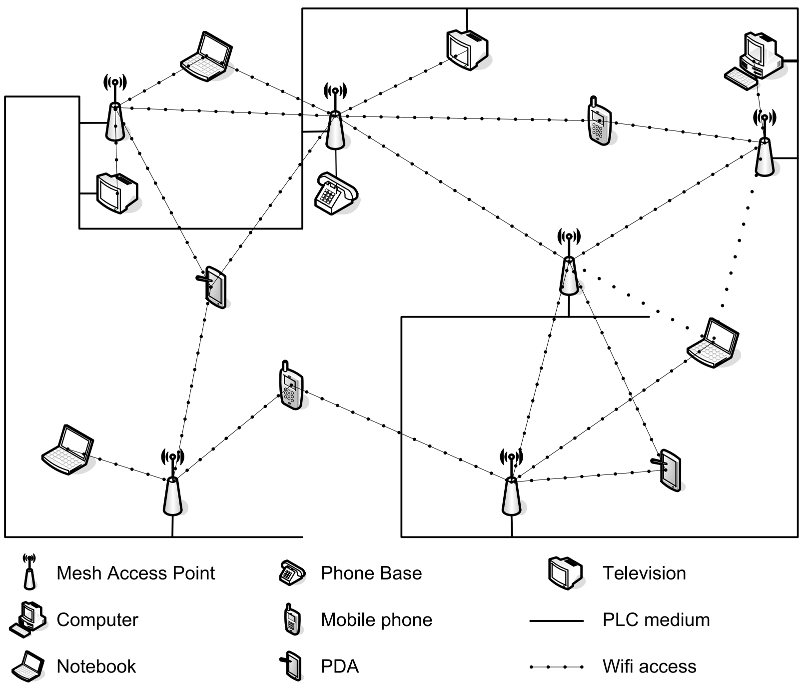

Fig. 1 Home Network architecture

2 A distributed knowledge plane for intelligent routing

The home network architecture described previously lies mainly on in-house telephone wiring, TV coaxial cable, existing power line, or radio frequency for wireless. These mediums are sensitive to electromagnetic noise, fading and interferences which introduce bandwidth fluctuations over time and make the QoS provision difficult to implement. We propose the use of a knowledge plane to overcome the aforementioned problem. This section briefly presents the knowledge plane concept and its implementation in the home context.

2.1 Why a knowledge plane?

The concept of knowledge plane in network was first introduced by David Clark [9, 10]. It was defined as a distributed and decentralized construct within the network that gathers, aggregates, and manages information about network behavior and operation. Clark's vision was to integrate self capabilities to the networks. Thus, the knowledge plane allows autonomic piloting of the standard control plane algorithms.

In the home context, the network should be aware of its resources state to provide an efficient routing and maintain the required QoS for critical flows. A knowledge plane is therefore necessary to enable a self adjustment of routing based on the ongoing application's requirements and available network resources.

To achieve this, we have designed a knowledge plane based on a multi-agent system, which provides a decentralized approach to solve problems in complex environments [16, 23]. One of the main ideas of multi-agent systems is to generate approximate solutions to complicated problems by distributing them to autonomous rational problem solvers called agents that have local problem solving capacities. So, the global issue comes from the cooperation between agents [13].

2.2 The knowledge plane framework description

Each network element (end device/MAP) has an embedded agent whose architecture is outlined in figure 2.

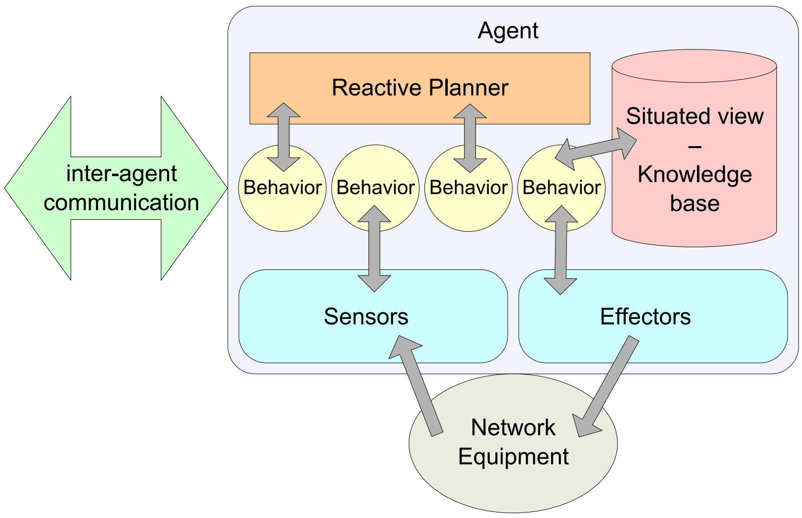

Fig. 2 Agent architecture

Each agent obtains and maintains a network view:

- directly from the network element
- indirectly via cooperative communication with other agents

Each agent thus has an updated knowledge of its close environment, essentially focused on its neighborhood. This knowledge base is called the *situated view* [7,18]. The agent's capabilities are defined as a set of behaviors. Behaviors are specialized functions used to perform agent's internal and external actions. They have access to the situated view which operates internally as a common blackboard. The agent's Reactive Planner triggers and dynamically schedules behaviors.

2.3 Knowledge plane based intelligent routing scheme

The routing process in home networks has to be reactive and adaptive to avoid service disruption for bandwidth sensitive applications such as video streaming and voice over IP. For each new flow created, the routing protocol will reserve the required resource all along the path. Once a route is established, agents of the knowledge plane cooperate to build an alternative solution in order to prevent any performance degradation.

2.3.1 Building the agent's situated view

The agent's situated view contains useful knowledge for the decision-making process. To accomplish its route restoration mission, the agent has to be aware of alternative routes to a destination that provide at least the same level of service as the current active one.

To gather this knowledge, agents exchange their node's routing table with peers from their situated view, limited to the one hop neighborhood. Based on received informations, each agent computes its alternative routing table (ART) that is made up of the best (in terms of available resources) alternative next hop. Those exchanges are made periodically in order to take into account recent routing table updates. Figure 3 outlines the ART derivation process.

2.3.2 Agent decision making process

The ART represents the agent's knowledge. Each time the required bandwidth is no longer available, the agent precedes the routing protocol to interrupt the signalization process. Instead of stopping flows as the routing protocol would have done, the agent replaces the faulty route with the alternative one provided by the ART. If this route does not exist, the routing protocol is resumed.

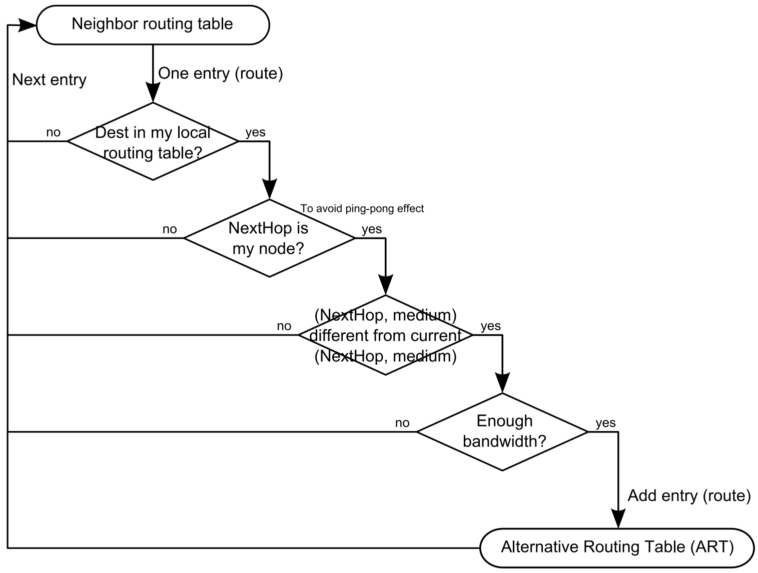

Fig. 3 ART derivation process

3 Testbed environment

3.1 Simulation

Sections 1 and 2 have presented the home network problematic and our proposal. A simulator has been implemented to evaluate our approach's relevance. A real testbed was not appropriate at this stage because we needed to focus on the problem's core complexity.

So far, we have been concentrating our efforts on two networking technologies: CPL and WiFi. Other wireless technologies can be added but this choice was made to simplify the simulation. However, these two dominant technologies raises most of common problems.

Our aim was to evaluate agents' efficiency facing the resource fluctuation problem and its ability to maintain QoS. We have chosen to implement a QoS-aware version of AODV (see [19, 20]), since we needed a functional network with a routing protocol in charge of building routes.

3.2 AODV implementation

The choice of AODV is justified as follows. In home networks, traffic can be approximated with flows: a user is downloading a file, is watching TV, is calling via it's VoIP phone... A reactive protocol, like AODV, is slower than a proactive one to open a flow because the route needs to be created before the first packet can be sent. Otherwise, flows in home networks are much longer than this initial phase duration. OLSR [11] could also be a pertinent choice, but we have preferred AODV, for industrial implementation reasons.

When a route has been computed, it is difficult to maintain it in a highly variable environment. This observation was made by [5] using a real testbed: *unstable* link causes poor AODV performance.

Otherwise, [12] compares AODV and DSR [17] and states that AODV outperforms DSR in a heavy load network, which is the case of home networks that must support high bandwidth flows from various sources (phone, TV, laptop, desktop, ...).

To support QoS in AODV, we have implemented [20] which is named AODV+ in the following. The purpose of this version is to mix RSVP [6] and AODV to create routes with a defined bandwidth (or delay). Until now, we have only considered QoS in terms of bandwidth, since this is the main criteria to ensure.

In the simulator, our aim was not to implement routing message exchanges, but to build the same routing tables as AODV+ would have done. Nevertheless we were interested in the route maintenance process, so we paid special attention to the implementation of this aspect.

3.3 Our simulator's capabilities

We have developed a simulator which allows us to represent a home network topology and to implement routing protocols and our knowledge plane, in order to evaluate our proposal's relevance. This simulator has been developed in Java 1.5 [3], in a modular way so that we can easily implement many specific environments. Nowadays, this includes a Graphical User Interface (GUI) which allows us to see information about:

- topology changes (mobile hosts can move, medium can suffer from interferences)
- existing flows
- nodes' routing tables, alternative routing tables
- routes creation, changes, ...

We can also prepare and execute precise scenarios, using Jython [4], including control of hosts's moves and mediums perturbations.

In this environment, we have represented the home network topology shown in figure 1 and executed a scenario which led to the following simulation cases.

4 Simulated cases

In this section, we are going to explain how the knowledge plane is built and how agents improve home networks reactivity when problems due to mobility or medium perturbations occur, and so, how agents pilot routing to ensure QoS.

We have seen that using a routing protocol alone is not always efficient in home networks. Indeed, AODV+ is not suitable to react quickly when a host is moving away from a MAP, or when interferences alter mediums quality.

By associating agents embedded in the network's nodes to AODV+, we managed to improve routing efficiency in some situations. Seeing that, an agent needs to know a few pieces of information:

- its parent's node routing table
- its neighbors' node routing tables

With those, an agent can find a suitable alternative route to reach each destination of its node's routing table. When a problem raises, the agent switches on this alternative route. We are now going to illustrate how it works with situations we have simulated.

4.1 First situation - Loss of access

The home network is made up of MAPs covering all the environment in which hosts, mobile or not, can be set.

An application generates a symmetric flow of 1 Mb/s between two hosts of the home network:

- the first one is not mobile, we call it *computer*
- the second one is mobile, we call it *mobile host*.

During the simulation, the application requests AODV+ to establish a route of 1 Mb/s between these two hosts. As shown in dotted line on figure 4, AODV+ creates this route, through two MAPs, B4 and B5. This route (going through B4 to reach the computer) is in the *mobile host*'s routing table, and the reverse one (going through B5 to reach the mobile host) is added in the *computer*'s routing table.

Among all flows, we can see one in figure 4 (pointed line) going from H9 to the computer through B1. So, this flow has added a route to the *computer* in B1's routing table.

The mobile host is moving away from B4 and heading toward B1. We are now going to explain how agents manage to keep the application running whereas the mobile host is going to lose its access to B4.

Every 10 seconds, the agent on each node updates its list of neighbors and sends them its current routing table.

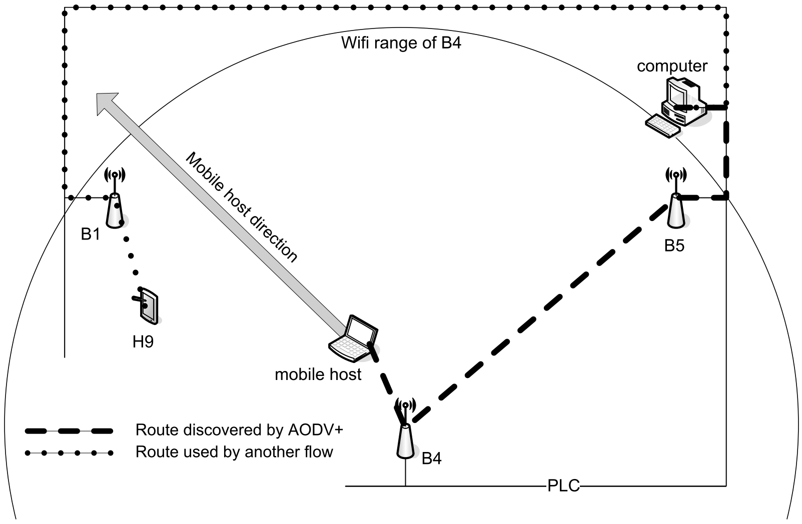

Fig. 4 Route discovered by AODV+

In our example, we focus on the *mobile host* which has two neighbors (B1 and B4) and so receives their routing tables shown in tables 1 and 2[1].

Dest	NextHop	Interface	Bandwidth
computer	computer	PLC	85 Mb/s
H9	H9	B1-wifi	23 Mb/s

Table 1 B1's routing table

Dest	NextHop	Interface	Bandwidth
mobileHost	mobileHost	B4-wifi	4 Mb/s
computer	B5	B4-wifi	16 Mb/s

Table 2 B4's routing table

The agent stores each received route into a local database called Neighbor Routing Info Base (NRIB), as illustrated in table 3.

Then, the agent scans its NRIB and, for each active route, it searches for an alternative one applying the ART derivation process illustrated in figure 3. According to the *mobile host*'s routing table shown in table 4, the agent has to find an alternative route to the *computer*.

[1] Only interesting routes are mentioned in tables.

SenderAgent	Dest	NextHop	Interface	Bandwidth
B1	computer	computer	PLC	85 Mb/s
B1	H9	H9	B1-wifi	23 Mb/s
B4	mobileHost	mobileHost	B4-wifi	4 Mb/s
B4	computer	B5	B4-wifi	16 Mb/s

Table 3 Mobile host's Neighbor Routing Info Base

Dest	NextHop	Interface	Bandwidth
computer	B4	B4-wifi	4 Mb/s

Table 4 Mobile host's routing table

While scanning its NRIB, the agent notices that both B1 and B4 have a route to the *computer*, but it excludes routes going through B4 because the current one already goes through this MAP. Finally, the agent deduces that going through B1 could be a good solution to reach the *computer* and, since the capacity is larger than the current one[2], it stores this route in its Alternative Routing Table (ART), shown in table 5.

Dest	NextHop	Interface	Bandwidth
computer	B1	B1-wifi	26 Mb/s

Table 5 Mobile host's Alternative Routing Table

In this way, when the *mobile host* loses its access to B4, the embedded agent looks up its ART to find an alternative route which is settled as the new active route, as indicated in figure 5. Thus, the application is not altered by this loss of access.

This process also works when a link does not offer the appropriate QoS anymore (because of an increasing distance between a host and its access point) or when mediums suffer interferences, as explained in the next part.

4.2 Second situation - Medium perturbation

We are now considering an application which needs a constant transfer rate of 10 Mb/s between the *computer* and the *mobile host*.

As shown in figure 6, a route (dotted line) that uses PLC has been established between these hosts. Another flow (pointed line) creates an entry to reach the *mobile host* in B4's routing table.

[2] At the moment, it is a required condition to add a route in the ART. This is subject to modification (see 6.1).

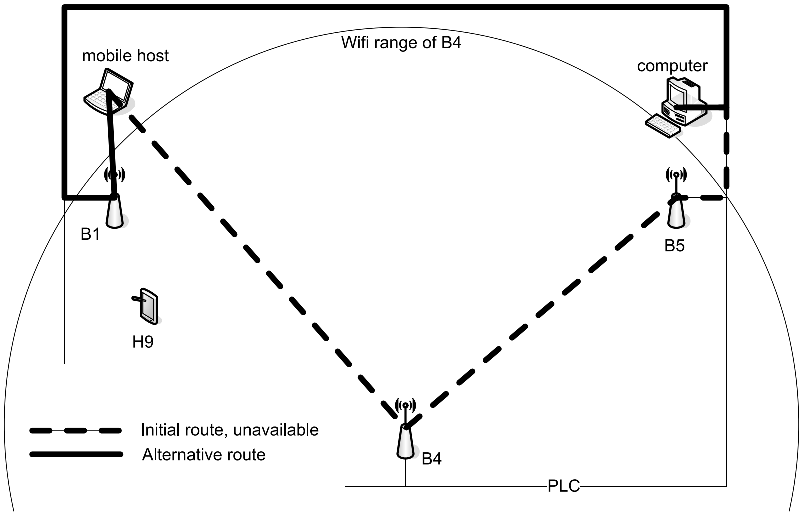

Fig. 5 Alternative route found thanks to agents

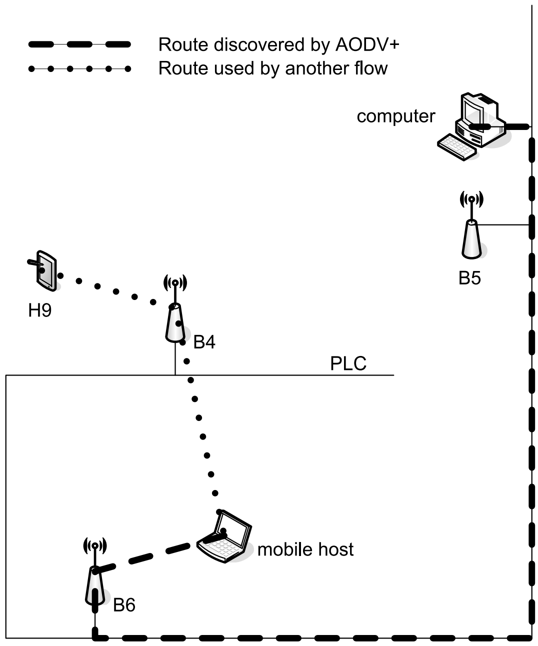

Fig. 6 Route discovered by AODV+

We are now going to simulate an interference on this PLC medium so that the available bandwidth on the route will no longer be sufficient for the 10 Mb/s flow.

Let's focus on the *computer*: we have said previously that B4 knows how to reach the *mobile host*. While receiving B4's routing table, the *computer*'s agent saves this route to the *mobile host* in its NRIB and later decides to store it into its ART.

When the PLC interference occurs, the current route can not satisfy the QoS anymore and the alternative route is settled in the *computer*'s routing table as shown in figure 7. Once more, our knowledge plane maintain the QoS, and the application is not perturbed.

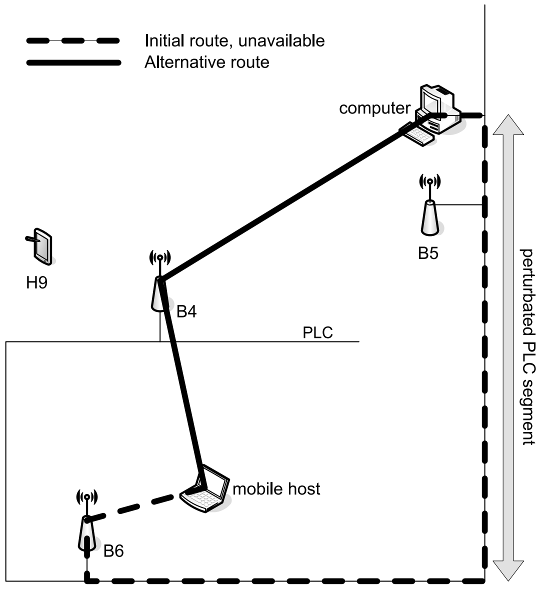

Fig. 7 Alternative route found thanks to agents

5 Results analysis

The previous section has explained how our routing scheme can improve AODV+ performance. This piloting system formed by agents is the first step of our implementation. With our simulator, we have noticed some deficiencies in AODV+. An enhanced knowledge plane will allow us to solve most of these problems.

During our simulation, we noticed two major problems. The first one, and probably the most complex is the bandwidth fluctuation in the reserved path. It is detailed in subsection 5.1. The second one concerns the way of handling path disruption, see subsection 5.2.

5.1 Bandwidth update problem

When AODV+ is building a route, the available bandwidth is set as the minimal value along the path. In a perturbation sensitive network, the bandwidth is constantly changing and there is no way to update it.

This point is tricky in the home network context, because of bandwidths unstability. An electromagnetic interference may temporarily alter both wireless and PLC links, and the QoS may no be longer satisfied. In this case, AODV+ specifies that the router sends an ICMP_QOS_LOST[3] packet to each source node which has to request a new route. If the bandwidth is increasing and decreasing quite fast, this may lead to an unstable convergence of AODV+, an important overhead and poor end-user performances.

The problem of QoS-aware routing in interference sensitive networks is complex and concerns other routing protocols as well as AODV+. There are many papers that mainly focus on bandwidth correlation: when a link is used, neighbors' ones are perturbed. This is an NP complex problem as concluded [8, 15, 24]. Apart from this problem, there are bandwidth fluctuations on links that may lead to unsatisfying QoS. Our routing scheme has to face this problem.

This problem has been eluded in our first simulations. Now that we have a functional testbed, we can take a closer look at this. We think that only agents can handle such a complexity and may be able to approximate the optimal solution. In routing protocols, there is a limited information exchanged between nodes. This can be improved with our knowledge plane, and the correct use of the situated view can handle more information. This is discussed in further details in section 6.

5.2 Route disruption

Beyond the QoS guarantee problem, there is a suboptimal mechanism in AODV+ due to its AODV's inheritance. When a link is no longer satisfying the reserved bandwidth, it specifies that each source of each route using it is notified by an ICMP_QOS_LOST message. This causes sources to reopen a new route (after a short disruption for the end-user).

It is harmful for overall performances to perturb each flow, whereas rerouting only one flow could solve the problem. For example, if there are 3 flows of respectively 5 Mb/s, 3 Mb/s and 1 Mb/s, the route is initially set to support 9 Mb/s. Due to an external event, the bandwidth falls down to 8 Mb/s. AODV+ is disrupting the 3 flows, whereas an *intelligent* action would have been to reroute the 1 Mb/s flow (admitting that this last flow is not more important than the others). In AODV+, there is no way to set priority, so the selection can only be done randomly (which can be disastrous for the overall performance).

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[3] Defined in [20] as to inform sources that the route no longer satisfies the initial QoS agreement

An approach *DiffServ*-like might help us in this case, as mentioned by [21] but we don't think it is directly usable in home networks. The need for an *ingress node*, in charge of classifying flows, is in contradiction with our decentralized view of the home network. In [22], the FQMM architecture is proposed, but the source node has to request for QoS, which means a deep modification of end devices. We would rather keep our architecture and investigate a solution based on our agents.

Agents can *learn* about flow types[4], regarding to source, destination, duration, bandwidth, ... Fuzzy logic may help agents to mix several criteria and select the best flow to be rerouted.

6 Future works

In the previous section, we mentioned some limitations inherent to QoS routing in perturbation sensitive environments. We think that our knowledge plane can considerably improve routing performance at a reasonable cost. Up to now, our implementation is quite simple, but already useful as explained in section 4.

However, there are several points to be enhanced. Initially, agents were designed to compute a better route than the current one. This point is now outdated as explained in subsection 6.1. Subsections 6.2 and 6.3 are purposes to enlarge information known by agents and can be used to improve decision algorithms.

6.1 Alternative route selection

So far, agents are selecting an alternative route when it is better than the current one. This may lead to an empty ART, which means that there is no alternative routes. If an interference occurs, agents are unable to find a quick solution, and so there is a flow disruption.

While writing agents' specifications, our aim was to improve AODV+ routing. However, we found out that in most cases the routing is sufficient. Problems arise with interferences, which means a fast modification of route's quality. The objective criterion of the *best* route is meaningless in those cases. That is why we are now focusing on building alternative routes as often as possible, even if the current one is better. This new approach corroborate AODV performance analysis of [5, 12].

[4] Basically, a flow between the Internet gateway and a VoIP phone is more important than a file transfer between PCs.

6.2 AODV+ stressing

For now, the alternative routes derivation process, illustrated on figure 3, is based on node's routing table. AODV is a reactive protocol, which means that routes are built on-demand. In a low-loaded network, there are only a few entries in the routing table, therefore agents know few alternative routes. In case of interferences, they are unable to rescue the routing protocol. This correlation between load and agent's performance is not satisfying.

Our solution is to stress AODV to build routes which can be done easily by generating regularly fake packets between agents. This action should be done only when the network is idling, and only for regions[5] with an obvious lack of alternative routes. This task can be fulfilled by our knowledge plane.

6.3 Mobility prediction

Situated views can solve yet another problem. We have concluded in section 5.2 that QoS in home networks is such a difficult problem that a protocol cannot solve by itself.

Our point is to manage this complexity with the knowledge plane, therefore we need to add information into agents to enable them to make complex decisions. A piece of information can be used for handover[6] prediction. [14] presents generic models for mobility prediction in wireless networks. Home networking is more specific because there are few access points and end devices as well as few handovers. A simple mechanism can be implemented into agents to *learn* about mobile hosts, and to anticipate disruptions.

Conclusion

To conclude, we can say that these first results are quite promising. Indeed, our first simulations have shown that our approach is realistic. There are, of course, some points to be improved. Nonetheless, our simulation enabled testing several routing protocols. AODV+ was the first protocol chosen, and we have pointed out some deficiencies 5.

We have concluded that these problems are far from being specific to AODV+, and that our knowledge plane is able to handle them. Indeed, agents can collect and manage more information than a routing protocol in order to extract useful

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[5] The concept of region is still to be defined, but we can reasonably established situated views on regions as a first approximation.

[6] The fact to change from on bridge to another

knowledge. So, this distributed *intelligence* may be able to approximate optimal solutions.

Our simulator grants us a complete control of the testbed, which will allow us to take a closer look on proposed improvements mentioned in 6.

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