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Song Yean Cho, Cedric Adjih, Philippe Jacquet

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Abstract: Wireless mesh networks (WMNs) consist of two kinds of nodes: mesh routers which form the backbones of WMNs and mesh clients which associate with mesh routers to access networks. Because of the discrepancy between mesh routers and mesh clients, WMNs have a hybrid structure. Their hybrid structure presents an opportunity to integrate WMNs with different networks such as wireless LAN, Bluetooth and sensor networks through bridging functions in mesh routers. Because of the ability to integrate various networks, WMNs are a potential candidate for ubiquitous networks. Organizing the WMNs to integrate heterogeneous networks requires two level of routing: routing tables for backbones between mesh routers, and association tables for linking mesh clients to mesh routers. In order to organize routing tables containing the computerd paths between mesh routers, mesh routers execute mesh routing protocols. However, the information in these routing tables is insufficient to find paths between mesh clients because they do not execute routing protocols. Hence, to complement routing tables, we store information about mesh clients in “association tables” indicating which mesh client is reachable by which router. To organize the association tables for all mesh clients, mesh routers should run an additional protocol. The association discovery protocol (ADP) that we propose operates efficiently. The proposed ADP focuses on decreasing control overhead without prolonging the delay to distribute association information to the entire network. The proposed ADP is evaluated by an analytical model and simulations.

Key-words: information exchange, association, hybrid wireless mesh, mobile ad hoc, OLSR.

Unité de recherche INRIA Rocquencourt
Domaine de Voluceau, Rocquencourt, BP 105, 78153 Le Chesnay Cedex (France)
Téléphone : +33 1 39 63 55 11 — Télécopie : +33 1 39 63 53 30

Un protocole de decouverte d'associations pour les Reseaux sans fil mailles hybrides Association Discovery Protocol for Hybrid Wireless Mesh Network

Résumé : Les réseaux sans fil maillés (Wireless Mesh Networks - WMNs) sont constitués de deux types de nœuds: les routeurs réseaux qui forment une épine dorsale et les clients réseaux qui s'associent à eux pour accèder au réseau. À cause de cette différence de statut entre routeurs réseaux et clients réseaux, les WMNs présentent une structure hybride. Cette structure hybride permet aux WMN d'intégrer des réseaux sans fil de technologies come WLAN, Bluetooth ou des réseaux de capteurs au travers de fonction de pontage par les routeurs réseaux. Grace à leur capacité d'intégrer des réseaux de natures diverses, les WMNs peuvent ainsi devenir des candidats sérieux pour des réseaux ambiants. L'extension des WMNs pour intégrer des réseaux hétérogènes nécessite des tables de routage et des tables d'association des clients réseaux. Ces tables contiennent les informations permettant d'identifier les chemins entre les routeurs réseaux, obtenus par l'exécution sur ces routeurs de protocoles de routage. La principale limitation des protocoles de routage provient du fait que les clients réseaux ne sont pas censés les exécuter. Pour subvenir à cette faiblesse, nous maintenons de l'information sur la position des clients réseaux dans les tables d'association. Ainsi, les routeurs réseaux exécutent un protocole de découverte d'association (Association Discovery Protocol - ADP). Le protocole ADP que nous proposons s'efforce de réduire la quantité de données échangées sans affecter le délai de distribution des informations dans le réseau. Nous évaluons notre solution par des modèles analytiques et par des simulations.

Mots-clés : échange d'information, association, réseau maillé sans fil hybride, mobile ad hoc, OLSR.

1 Introduction

Wireless Mesh Networks (WMNs) have been proposed as a prominent network solution for ubiquitous networks[1], and industry standard groups such as IEEE 802.11[2][3] [4], 802.15[5] and 802.16[6] are working new specifications for WMNs. The recent intensive research about MMNs are based on two major features of WMNs. First, WMNs are self-configuring and self-healing. WMNs are composed of mesh routers which assist each other in forwarding packets. To organize multi-hop networks automatically, mesh routers detect their neighbors, gather topology information and organize routing tables. This is done by means of a routing protocol, such as MANET routing protocols. Through these operations, WMNs are organized without requiring network administrators, and can be deployed with minimal preparation. Second, WMNs enable mesh clients to access networks even if mesh clients cannot execute these operations for self-configuration and self-healing. Instead of these more complex routing protocol operations, mesh clients simply associate themselves with mesh routers and rely on them to access the whole WMNs. To permit the mesh clients' participation, a hybrid structure is indispensable, with mesh routers on one level, and mesh clients on the other level. In addition, this structure presents another opportunity to connect heterogeneous networks. In other words, the hybrid structure enables mesh routers not only to forward data but also to find paths for mesh clients in heterogenous networks.

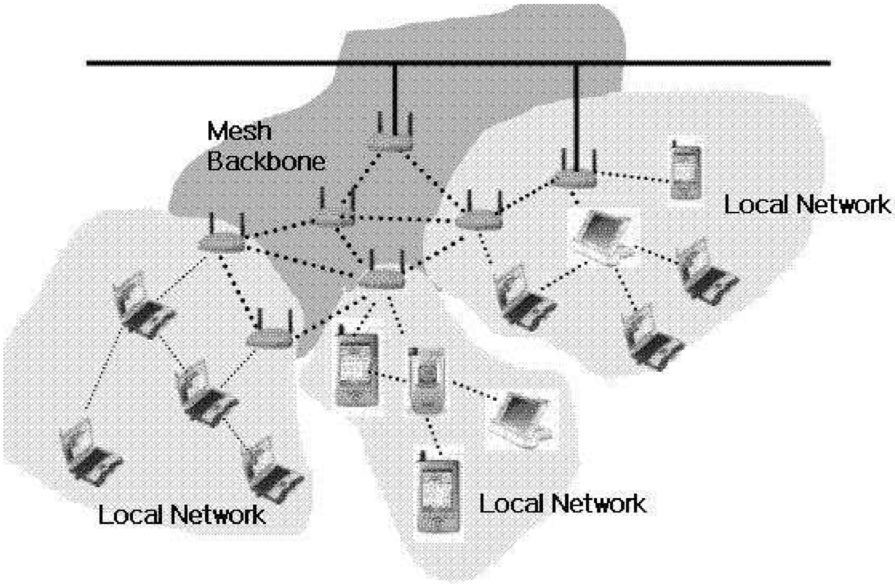

Figure 1: Architecture of hybrid wireless mesh networks

As shown in figure 1, WMNs consist of two parts: the backbone and the client networks. The backbone is composed of mesh routers. To form the backbone, mesh routers run a routing protocol, which results into computation of routing tables. The routing protocols for WMNs are not much different from those of wireless ad hoc network in general and Mobile Ad hoc NETwork (MANET) [15] in particular. For MANET, several routing protocols such as OLSR [7], AODV [8], TBRPF [10] and DSR [9] have been proposed, thus we can utilize these protocols for WMNs. Figure 1 shows client networks which are connected through mesh routers. For these connections, mesh routers should associate with mesh clients they must support. To solicit mesh routers' support, mesh clients associate with a mesh router using a specific attachment protocols such as page/inquiry for Bluetooth or association request/reply for IEEE 802.11.

The mesh clients' participation in WMNs leads to a different mode of operations from that of the classical MANET protocols. Information exchanged by MANET routing protocols is for a flat topology. Thus the information is insufficient for transferring data between mesh clients. To collect complementary information, mesh clients execute additional operations, to provide the necessary extra information to the mesh routers: an "association protocol". The "Association Discovery Protocol" (ADP) proposed in this article is one such efficient protocol. Hence, mesh routers in our solution execute two protocols: the mesh routing protocol and the ADP. By executing these two protocols, mesh routers can compute both routes (hence the routing table) to other mesh routers, and routes to the mesh clients associated by to these other mesh routers (by means of an "association table").

This article is organized as follows. First we explain related work. Next we briefly explain how the OLSR routing protocol operates to compute routing tables for all mesh routers, and then we describe the ADP proposed working in conjunction with OLSR. Afterwards, we estimate the performance of the ADP through an analytical model and evaluate our estimation through simulations. After presenting and analyzing simulation results, we present our conclusion.

2 Related Work

A hybrid network structure is not a unique feature of WMNs. The hybrid routing protocols such as FSR [11], ZRP [12] or CBRP [13] have been explored for MANETs with a similar hybrid structure. But their hybrid structure is different from that of WMNs in two aspects: the presence of non-router nodes and the use of a flat address space.

- **Non-router nodes:** In most traditional hybrid routing protocols, every node participating in the MANET is supposed to act as a router. In other words, every participant runs the routing protocol, even though some nodes operate with different levels of responsibility. For example, a network can be divided into several clusters. Nodes inside each divided part are responsible for routing inside its own part, and only special nodes in each part must execute routing protocol for the whole network. In this case, scalability causes WMNs to assign different levels of responsibility to nodes. Unlike this case, different capabilities between mesh router and mesh client lead WMNs to assign different levels of responsibility.

- **Flat address space:** In many ad hoc routing protocols, layer 3 addresses are used (i.e., IPv4 or IPv6 addresses), and some hybrid approaches rely on the address aggregation provided by the IP address world for creating a hierarchical structure. To be precise, in order to reach a destination address, an intermediary router may find a route which does not specify the destination address itself, but the prefix of a network including the address. In WMNs, mesh clients in heterogeneous network are connected through mesh routers, and they can use non-IP addresses such as hardware addresses. Non-IP addressing can prevent address aggregation and requires flat routing. In flat routing, the routes to every mesh client should be known, and information about mesh clients should be exchanged. The ADP provides efficient way to exchange information about mesh clients

To permit nodes without routing functions, OLSR also provides a mechanism called *Host and Network Association* (*HNA*) to exchange information about routes to non-OLSR nodes. However, in the current specification [7], HNA in [7] is not well adapted to non-OLSR nodes for which the last hop (an OLSR node) may be changing quickly. An OLSR node periodically distributes HNA messages listing all non OLSR nodes. In addition, a mesh router associates with several mesh clients in WMNs, and the lists in its HNA messages can become long. Moreover, mesh clients listed in HNA messages changes according to the mesh clients' mobility. In worse cases, the control overhead from HNA messages can become dominant over the control overhead of the routing protocol between mesh routers. Because of this control overhead, we need an efficient way to decrease control overhead.

Concerning other related works, more general protocols exist to diffuse distributed sets of information, such as OSPF-style database exchange for OLSR [16], Gossip-based approaches [17] and on-demand request/response for reactive protocols. Unlike these protocols our protocol is specifically designed to address the following information exchange problems:

- Information items (which mesh client is associated to which mesh router) with sequence numbers
- Medium-sized information set (potentially too large to be diffused periodically, but for which a single level of hierarchy is sufficient)

The main feature of ADP proposed is to limit the overhead of repeating information which is already widely known. Executing ADP with OLSR, we can provide another optimization with OLSR's optimization. This optimization by OLSR and ADP can save bandwidth, an critical resource in wireless networks. In the next section, we explain OLSR briefly.

3 OLSR Routing Protocol

The OLSR routing protocol, used to select paths in WMNs, is a proactive link-state routing protocol, employing periodic message exchanges to update topological information in each mesh router. Because OLSR is specifically designed to operate in the context of wireless multi-hop networks such as MANET, it provides an optimized flooding mechanism, called

MultiPoint Relay (MPR)-flooding, used to diffuse topology information. MPR flooding optimizes flooding by minimizing the redundant retransmissions of Topology Control (TC) messages. Minimization is achieved by limiting the forwarders of messages to some MPRs. A set of MPRs relays is a small set of neighbors through which a sender can reach all two hop neighbors.

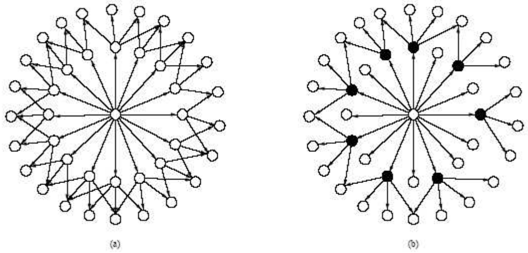

Figure 2: Pure flooding vs. MPR flooding

As figure 2 shows, messages can be broadcasted from the source to the entire WMNs through MPRs' relaying. Setting up the paths may not require all links between mesh routers. Information about links with MPRs is sufficient, by property of the MPR (and because all nodes have selected an MPR set). Thus mesh routers can simply transmit the addresses of all their MPR selectors with their address in TC messages. Even if the topology information obtained from received TC messages is a partial topology of whole WMN, the shortest path obtained from this partial topology has the same length as the shortest path from the full topology [14].

Now, considering the hybrid structure of WMNs, the association between mesh clients and mesh routers must be discovered in order to complement the topology information of the mesh routers.

4 Association Discovery Protocol

The base mechanism of ADP is to diffuse the whole set of mesh clients associated to a mesh router. For optimization, the proposed ADP limits the overhead of repeating information which is already widely known. This limitation brings an interesting trade-off between bandwidth use and reactivity to changes.

As explained in **??**, mesh clients rely on mesh routers to compute paths to their destination, and this computation requires both routing tables and association tables. To organize the two type of tables, mesh routers transmit information about mesh clients associated with themselves along with the traditional information from the routing protocol. Because the distributed information must be used when computing routes to mesh clients, mesh routers store and maintain the received information using two information bases:

- *Local Association Base (LAB):* Each mesh router keeps track of mesh clients associated with itself. This information base is updated whenever associated mesh clients leave or new mesh clients join. Additionally, to provide support for a large number of mesh clients, each mesh router can divide its LAB into several blocks and distribute them block by block if the need arises.
- *Global Association Base (GAB):* Each mesh router maintains a GAB to record which station is associated to which mesh router in the entire WMNs. Upon receiving LAB from all other mesh routers, the GAP is updated. Hence the GAB should contain the union of the all LAB, of each mesh router in WMNs.

As described above, the mesh routers distribute their full LAB periodically but these control messages create additional overhead. Considering that a LAB is not modified when there is no new association or disassociation, all mesh routers need not distribute their full LAB every time. An important issue is to decrease the amount of control messages exchanged in the whole WMNs without dramatically decreasing the reactivity of the protocol in response to the mobility of associated stations. To achieve the two goals of keeping consistency and decreasing overhead, the ADP proposed provides two operating modes: *full* and *checksum*.

Initially a Mesh router operates in full mode. If the mesh router does not sense any change in its LAB, the mesh router starts to operate in checksum mode. Any change in its LAB sets the mesh router back to operate in full mode.

4.1 Full Mode

As previously described, every mesh router keeps a set of associated mesh clients in its LAB as a result of the mesh client's association according to its protocol. In full mode, the mesh router periodically broadcasts the whole contents of its LAB. Each mesh router populates its GAB by processing these messages issued in full mode. Using their GAB together with their OLSR routing table, mesh routers can compute routes to every mesh client.

4.2 Checksum Mode

As wireless multi-hop communication is basically unreliable, it is hard to avoid periodic broadcasting of LAB in full mode despite its heavy overhead. If the network becomes stable and few mesh clients are moving, the LAB of mesh routers will not change much. In this case, mesh routers avoid generating heavy overhead by simply diffusing checksums representing the status of their LAB rather than sending the all its content. Upon receiving these checksums, a receiving mesh router cannot populate entries in its GAB, but it can verify them. To verify GAB, a mesh router looks for entries corresponding to the message originator. If such entries are found, the mesh router computes the associated checksums and compares them to the received checksums. If a checksum mismatch is found, this implies that the mesh router has missed some updates of the LAB of the mesh router which originated the message. In this case, the mesh router will send a request for the mismatching parts to originator mesh router in order to restore the consistency of its GAB by recovering the lost information. Upon receiving these requests, the mesh router switches to full mode, thus emitting the contents of its whole LAB.

5 Analytical Model

An analytical model of the ADP enables us to predict the protocol's performance. This model provides an approximate analysis of packet error rate (PER) on account of lost control messages and of the additional overhead to distribute LAB. Mesh clients move independently and their movements are not synchronized. In our model, data packets are assumed to be lost only when mesh clients move from the sojourned mesh router and notifications of this movement is lost. This assumption aims to remove other causes of packet loss between two mesh clients. The loss time when the position of mesh clients is not known is shorter than the sojourn time when mesh clients associate with the mesh router. Before modeling ADP's performance, we analyze network conditions to fully utilize ADP. Under the analyzed conditions, we present a formula to estimate ADP's performance through PER and control overhead.

5.1 Mode Switching

ADP can decrease overhead as long as it operates in checksum mode. To evaluate how and when ADP can decrease overhead, we should estimate the possibility that mesh routers execute ADP in checksum mode. Mesh routers change their operation mode from full to checksum when their LABs do not change for h_i x t_i, where h_i is mesh router i's control message distribution interval and t_i is the number of message intervals required to switch mesh router i's operation mode from full to checksum. In other words, the possibility changes according to mesh client's mobility, i.e. , life time and frequency. Life time (L_i^α) is the time a mesh client α associates with a mesh router i. Frequency (τ_i^α) is the number showing how often a mesh client α sojourns with mesh router i. If mesh clients move from one mesh client to another mesh client with Poisson distribution, the possibility that mesh router i's LAB does not change for (h_i) is

$$e^{-(2\frac{M_i}{L_i})h_i} \tag{1}$$

In expression 1, e is the base of the natural system of logarithms and M_i is number of mesh clients associated with mesh router i. M_i is the related with mesh clients' mobility and the number of associated mesh clients. More precisely, M_i is $N \times \tau_i L_i$, where N is the total number of mesh clients. Similar to τ_i^α and L_i^α, τ_i is the sum of sojourned number of all mesh clients to associate with mesh router i, and L_i is the sum of sojourned time of all mesh clients to associate with mesh router i. As a result, the possibility that a mesh router i operates in checksum mode $P^i_{checksum}$ is

$$e^{-(2N\times\tau_i\times h_i)\times t_i} \tag{2}$$

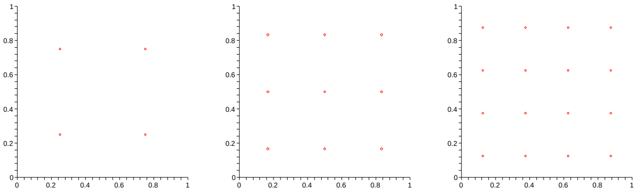

Figure 3: mesh routers in grids

As expression 2 shows, $P^i_{checksum}$ increases if τ_i becomes lower. In 2, h_i and t_i do not change while running ADP. When h_i and t_i are fixed, the main factor to change $P^i_{checksum}$ is τ_i. To find their relationship in detail, we compute $P^i_{checksum}$ is τ_i when mesh routers stay in grids like figure 3. In computation, h_i equals 2 seconds and t_i equals 3.

Table 1: high mobility and possibility to operate in checksum mode

τ_i^α				
mobillity	0.1	0.2	0.3	0.4
2x2 grid	0.0084	0.0252	0.0421	0.0589
3x3 grid	0.0033	0.0099	0.0164	0.0230
4x4 grid	0.0016	0.0047	0.0078	0.0000
$P^i_{checksum}$				
mobillity	0.1	0.2	0.3	0.4
2x2 grid	0.1993	0.0079	0.0003	0.0000
3x3 grid	0.0408	0.0001	0.0000	0.0000
4x4 grid	0.0083	0.0000	0.0000	0.0000

Because the total area for each grid in figure 3 is 1, the transmission ranges of a mesh router in 2x2, 3x3 and 4x4 grid are 0.53, 0.35 and 0.26, respectively. When we assign a mesh client α to each mesh router and move each mesh client 0.1, 0.2, 0.3 and 0.4 of transmission range per second, τ_i^α and $P^i_{checksum}$ changes as in table 1.

Table 1 confirms that a mesh router operates in full mode almost all the time if the mesh clients move fast. The fast movement causes mesh clients to roam frequently from one mesh router to another mesh router and to sojourn with one mesh router at a shorter time than before. In other words, L_i^α decreases and τ_i^α increases. The changes of L_i^α and τ_i^α update mesh routers' LAB frequently. The frequent updates finally bring down the possibility for mesh router to operate in checksum mode as seen in table 5.1. This is the reason why $P^i_{checksum}$ approaches zero.

The noticeable fact in table 1 is that the possibility for mesh routers to operate in checksum is not distinct according to mobility. This indistinguishability results from the extremly mobility of mesh clients in table 1.

Table 2: low mobility and possibility to operate in checksum mode

τ_i^α				
mobillity	0.01	0.03	0.05	0.07
2x2 grid	0.0008	0.0025	0.0042	0.0059
3x3 grid	0.0003	0.0010	0.0016	0.0023
4x4 grid	0.0002	0.0005	0.0008	0.0011
$P^i_{checksum}$				
mobillity	0.01	0.03	0.05	0.07
2x2 grid	0.6164	0.2342	0.0885	0.0336
3x3 grid	0.3831	0.0562	0.0084	0.0012
4x4 grid	0.2375	0.0134	0.0008	0.0000

To fully utilize ADP and to obtain benefits, mesh routers execute ADP in checksum mode long enough to decrease overhead. For sufficient time, the mobility of mesh clients should be lower than mobility in table 1. Thus we slow down the mesh clients' speed as in table 5.1 and increase the number of mesh clients to 3 × mesh router's number. As table 2 shows, $P^i_{checksum}$ is above 0.2 if mesh client α moves shorter than 0.05 x transmission range a second. These results show that a mesh router may execute ADP in checksum mode for a longer time than in full mode if τ_i^α is +-0.0025 when h_i is 2 seconds and t_i is 3.

5.2 Packet Error Rate (PER)

Under the analyzed condition in 5.1, we estimate PERs. To estimate Packet Error Rate (PER), our model utilizes τ_i^α and L_i^α.

When loss probability of control messages between mesh router i (r_{ij}) and mesh router j is known, the average loss interval between mesh router i and mesh router j is $\frac{h_j}{1-r_{ij}}$. As mesh client α sojourns with mesh router i for L_i^α with τ_i^α frequency, mesh router i can find a random mesh client α with the probability $\tau_i^\alpha L_i^\alpha$, where the sum of $\tau_i^\alpha L_i^\alpha$ for all mesh routers equals 1.

Considering all cases where a mesh client α can be located, the average loss interval between any two mesh routers is

$$\sum_{i,i \neq j} \frac{h_j}{1 - r_{ij}} \tau_i^\alpha L_i^\alpha \tag{3}$$

A mesh client β stays for an average time L_j^β, thus the loss rate from mesh client α to mesh client β is

$$\sum_{(i,j),i\neq j} \tau_i^\alpha L_i^\alpha \frac{h_j}{1-r_{ij}} \tau_j^\beta \tag{4}$$

To estimate PER, we also need to know τ_i^α and L_i^α. Because we use the random walk model to move mesh clients, τ_i^α is related to the area where mesh routers cover. More precisely, $\tau_i^\alpha L_i^\alpha$ is equals to $\frac{A_i}{A}$, where the total network area is A and mesh router i covers A_i area.

The frequency with which mesh client α sojourns with mesh router i (τ_i^α) is proportional to B_i, the border of mesh router i's area A_i. When mesh client α moves at speed v^α, the probability that mesh client α crosses the border on the portion $d\lambda$ during time interval $(t, t+d\lambda)$ is

$$\frac{d\lambda sin\theta}{2\pi Ar} rdr \tag{5}$$

At time t, mesh client α must be in the half of the disk of radius $v^\alpha dt$ and moves toward the portion $d\lambda$. Considering the mesh client α at a distance between r and $r+dr$ in the cone at angle θ, the probability that mesh client α is within this area is $\frac{rdrd\theta}{A}$. The angle at which mesh client α sees the portion $d\lambda$ is $\frac{d\lambda sin\theta}{r}$ and the speed of mesh client α toward this direction is probably $\frac{d\lambda sin\theta}{2\pi r}$. Therefore the probability that mesh client α crosses the border on the portion $d\lambda$ during the time dt is:

$$\int_0^\pi d\theta \int_0^{vdt} \frac{d\lambda sin\theta}{2\pi Ar} rdr = \frac{v^\alpha d\lambda}{\pi A} \tag{6}$$

On the total border length B_i, the probability that the mesh client α crosses B_i becomes $\frac{v^\alpha \times B_i}{\pi A}$. Consequently packet error rate between the mesh client α and β, $PER_{\alpha\beta}$ is equals to

$$\sum_{(i,j)i\neq j} \frac{v^\alpha \times B_i}{\pi A} L_i^\alpha \times \frac{h_j}{1-r_{ij}} \times \frac{v^\beta \times B_i}{\pi A} \tag{7}$$

If mesh router i distributes its LBA at different intervals depending on its operating mode, $PER_{\alpha\beta}$ must be computed separately with the possibility that the mesh router operates in full mode and checksum mode, then these results must be added. In our model, the interval to distribute the control message is the same for both operation modes. Therefore, $PER_{\alpha\beta}$ of our model is like the above formula even if we consider mode switching.

5.3 Control Overhead

When mesh router i operates in full mode, the size of the control messages to distribute LAB is proportional to the average number of mesh clients associated with mesh router i. In contrast, the overhead from checksum mode operations does not change and the amount of overhead is determined by hash function generating checksum regardless of the number of mesh clients. If ADP represents each mesh client in C_1 bytes and the hash function to generate checksum outputs C_2 bytes, the decreased overhead per h_i by introducing checksum mode is

$$C_1 M_i - C_1 P^i_{full} M_i + C_2 P^i_{checksum} = P^i_{checksum}(C_1 M_i - C_2) \tag{8}$$

As expression 8 shows, the overhead from mesh router starts to decrease if M_i is greater than $fracC_1C_2$. If $C_1 = C_2$, the control overhead decreases if the mesh clients just outnumber the mesh routers. This overhead decrease is also related to the mesh client's mobility, L^α_i and τ^α_j. As mesh client α sojourns with mesh router i for L^α_i with τ^α_j frequency, the average number of mesh clients associated with mesh router i (M_i) equals $\sum_\alpha \tau^\alpha_j L^\alpha_j$. Combining this with 8, the overhead decrease equals

$$P^i_{checksum}(C_1 \sum_\alpha \tau^\alpha_j L^\alpha_j - C_2) \tag{9}$$

6 Simulation

We have performed simulations to evaluate our analytical model and the ADP itself. To evaluate our analytical model, we compare the PER and the control overhead estimated by our model with the measured ones in simulations. On the other hand, we study ADP itself in two aspects: performance and cost. To analyze ADP's performance, we compare PERs generated by mesh router executing ADP with PERs generated by mesh router operating only in full mode. On the other hand, we measure the amount of control overhead between these two kinds of nodes. We execute simulations with parameters in table 3. To remove other factors affecting PER and control overhead, Null MAC is used.

Table 3: Simulation and scenario parameters

Simulation Parameters	
Control msg loss rate per link	0.1
Mobile station num	3 x Mesh AP num
Control message interval	2 sec
Interval num to switch mode	3
Transmission range between Mesh routers	0.53(2x2), 0.35(3x3), 0.26(4x4)
Scenario Parameters	
802.11 legacy stations speed	0.01,0.03,0.05 x TR
Simulation time	20000 sec
Mobility model	Random walk
Pause time	5 sec
Taffic pattern	constant bit rate, 512 bps
max connection	0.1 x mesh client num

According to our analytical model, ADP brings more benefits on condition that the mesh client moves slower than +-0.0025 × transmission range per second and more than one mesh client associate with a mesh router. This analytical result leads us to simulate focusing on dense networks with slow moving mesh clients.

In addition, we estimate PERs between any two mesh clients using our analytical model. As the mobility of the mesh client increases and the number of mesh routers decreases, our model underestimates PERs as seen in figure 4. At the same time, the average gap between estimated PERs and measured PERs becomes larger, but at least 0.003 and only at most 0.0007, even if the gap increases. These small gaps show that the PERs estimated by our model are close to the real PERs.

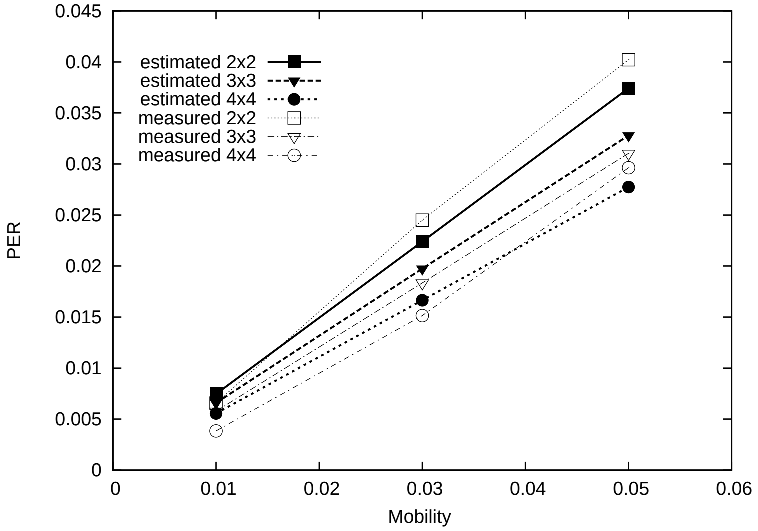

Figure 4: comparison between estimated and measured PERs

If a mesh router does not use ADP, it always distributes a whole LAB. Distributing a whole LAB can improve PER, but consumes considerable bandwidth. To measure how much PER has improved by distributing a whole LAB, we compare PERs from a mesh router executing ADP with PERs from a mesh router distributing whole LAB. Figure 5 shows PERs from these two kinds of mesh routers. PERs from a mesh router using ADP is slightly lower than other, but their difference is just less than 0.002. This small improvement shows that ADP allows mesh router to keep its PERs at the same level when it distributes whole LAB all the time.

While keeping its performance as described above, ADP decreases the control overhead as shown in figure 6 for control message distribution interval h_i. If a mesh client moves slower than 0.05 x transmission range per a second, for example at 0.003 x transmission

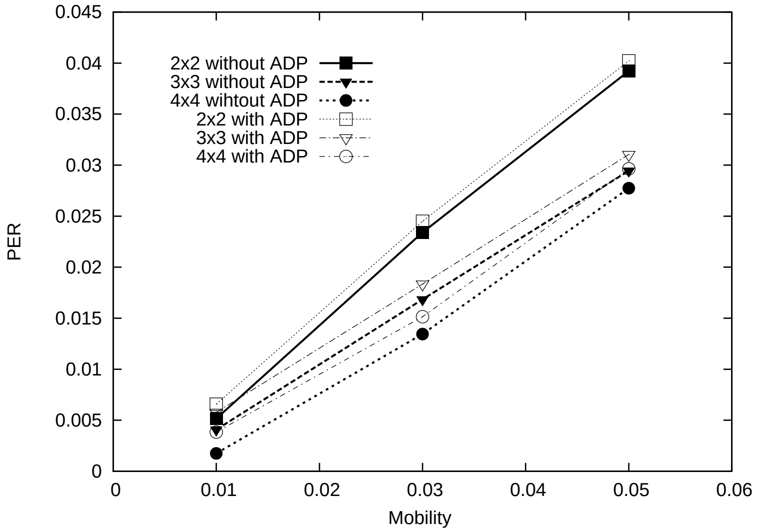

Figure 5: comparison of PERs with and without ADP optimization

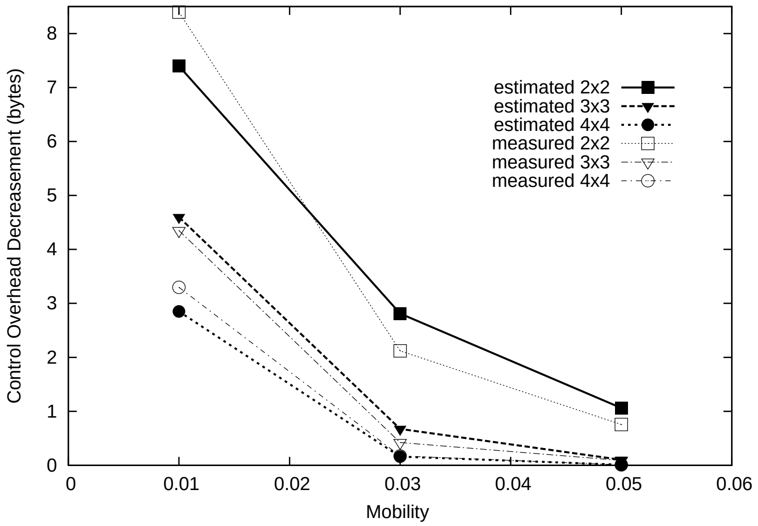

Figure 6: Control overhead decrease

range, the control overhead decreases from 8 to 2 bytes per control message distribution interval h_i as estimated by our model. The fact that the mesh router can decrease the control overhead using ADP supports the fact that ADP saves bandwidth by optimizing the control messages to distribute LAB.

In figure 6, control overhead decreases to almost zero with 0.05 mobility in grid 4x4. This overhead fall is due to the dramatic decrease in the possibility that mesh router i operates in checksum mode. As analyzed by our model, speeding up mesh client faster than 0.05 $times$ transmission range per second negates the possibility for a mesh router to operate in checksum mode and to decrease the control overhead by utilizing ADP. This result demonstrates the accuracy of the estimation made by our model on the control overhead. Simulation results in figure 6 also confirm this. Moreover, the control overhead decrease also shows that ADP saves bandwidth by optimizing control message to distribute LAB.

The only unexpected feature in figure 6 is that the control overhead fall slows down as the number of mesh client per Mesh router increases. This feature results from the fact that this decrease in figure 6 is caused by only one mesh router. If we consider all mesh routers, we multiply the number of mesh routers with the amount of control overhead decrease. In the product, the total control overhead decreases as more mesh clients join the network, just as we have analyzed in our model.

7 Conclusion

In the architecture that we have proposed, the mesh routers must execute not only a routing protocol to calculate their routing table but also an ADP, Association Discovery Protocol, to distribute the list of mesh clients associated with them. In distributing the list of mesh clients associated with mesh routers, we encounter the challenge of how to decrease the additional control overhead. This additional control overhead cannot be ignored because a mesh router can associate with a large number of mesh clients. In addition, finding paths between two mesh clients demands that the mesh router should know the entire lists of mesh clients associated with other mesh routers. Thus the mesh router should periodically distribute information about all mesh clients associated with them. In this case, the additional overhead to distribute information can become larger than the overhead from the wireless mesh routing protocol. This may happen if the wireless mesh network has more mesh clients and the mesh clients roam frequently.

To answer this challenge, the proposed ADP switches operating modes depending on the status of LAB and GAB (tables holding the entries about the associated mesh clients). If the LAB becomes stable, a mesh router in full mode will switch its mode to checksum mode, issuing only checksums to represent the content of its LAB. As the analytical model and simulation results show, switching between full and checksum modes reduces the additional control overhead of ADP while keeping LABs consistent in the entire wireless LAN. In addition, ADP becomes more beneficial when a mesh router associates with more mesh clients and mesh clients move slower than 0.03 x transmission range per a second. In synthesis, the ADP proposed supports hybrid wireless mesh networks with low overhead.

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Unité de recherche INRIA Rocquencourt
Domaine de Voluceau - Rocquencourt - BP 105 - 78153 Le Chesnay Cedex (France)

Unité de recherche INRIA Lorraine : LORIA, Technopôle de Nancy-Brabois - Campus scientifique
615, rue du Jardin Botanique - BP 101 - 54602 Villers-lès-Nancy Cedex (France)
Unité de recherche INRIA Rennes : IRISA, Campus universitaire de Beaulieu - 35042 Rennes Cedex (France)
Unité de recherche INRIA Rhône-Alpes : 655, avenue de l'Europe - 38330 Montbonnot-St-Martin (France)
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Éditeur
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