Dynamic Layouts for Wireless ATM*

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Abstract. In this paper we present a new model able to combine quality of service (QoS) and mobility aspects in wireless ATM networks. Namely, besides the standard parameters of the basic ATM layouts, we introduce a new one, that estimates the time needed to reconstruct the virtual channel of a wireless user when it moves through the network. QoS guarantee dictates that the rerouting phase must be imperceptible. Therefore, a natural combinatorial problem arises in which suitable trade-offs must be determined between the different performance measures. We first show that deciding the existence of a layout with maximum hop count h, load l and distance d is NP-complete, even in the very restricted case $h = 2$, $l = 1$ and $d = 1$. We then provide optimal layout constructions for basic interconnection networks, such as chains and rings.

1 Introduction

Wireless ATM networks are emerging as one of the most promising technologies able to support users mobility while maintaining the QoS offered by the classical ATM protocol for Broadband ISDN [2]. The mobility extension of ATM gives rise to two main application scenarios, called respectively *End-to-End* WATM and WATM *Interworking* [13]. While the former provides seamless extension of ATM capabilities to users by allowing ATM connections that extend until the mobile terminals, the latter represents an intermediate solution used primarily for high-speed transport over network backbones by exploiting the basic ATM protocol with additional mobility control capabilities. Wireless independent subnets are connected at the borders of the network backbone by means of specified ATM interface nodes, and users are allowed to move among the different wireless

* Work supported by the IST Programme of the EU under contract number IST-1999-14186 (ALCOM-FT), by the EU RTN project ARACNE, by the Italian project REAL-WINE, partially funded by the Italian Ministry of Education, University and Research, by the French MASCOTTE project I3S-CNRS/INRIA/Univ. Nice–Sophia Antipolis and by the Italian CNR project CNRG003EF8 – "Algoritmi per Wireless Networks" (AL-WINE).

H. Kosch, L. Böszörményi, H. Hellwagner (Eds.): Euro-Par 2003, LNCS 2790, pp. 1056–1063, 2003.

subnets. In both scenarios, the mobility facility requires the efficient solution of several problems, such as handover (users movement), routing, location management, connection control and so forth. A detailed discussion of these and other related issues can be found in [13,6,5,19,17].

The classical ATM protocol for Broadband ISDN is based on two types of predetermined routes in the network: *virtual paths* or VPs, constituted by a sequence of successive edges or physical links, and *virtual channels* or VCs, each given by the concatenation of a proper sequence of VPs [15,14,18]. Routing in virtual paths can be performed very efficiently by dedicated hardware, while a message passing from one virtual path to another one requires more complex and slower elaboration.

A graph theoretical model related to this ATM design problem has been first proposed in [12,7]. In such a framework, the VP layouts determined by the VPs constructed on the network are evaluated mainly with respect to two different cost measures: the *hop count*, that is the maximum number of VPs belonging to a VC, which represents the number of VP changes of messages along their route to the destination, and the *load*, given by the maximum number of virtual paths sharing an edge, that determines the size of the VP routing tables (see, e.g., [8]). For further details and technical justifications of the model for ATM networks see for instance [1,12].

While the problem of determining VP layouts with bounded hop count and load is NP-hard under different assumptions [12,9], many optimal and near optimal constructions have been given for various interconnection networks such as chain, trees, grids and so forth [7,16,10,11,20,4] (see [21] for a survey).

In this paper we mainly focus on handover management issues in wireless ATM. In fact, they are of fundamental importance, as the virtual channels must be continually modified due to the terminals movements during the lifetime of a connection. In particular, we extend the model of [12,7] in order to combine QoS and mobility aspects in wireless ATM networks.

Typical handover managements issues are the path extension scheme, in which a VC is always extended by a virtual path during a handover [5], or the anchor-based rerouting and the nearest common node rerouting [13,3], that involve the deletion of all the VPs of the old VC and the addition of all the VPs of the new one after a common prefix of the two VCs. Other handover strategies can be found in [13,6,5].

Starting from the above observations, besides the standard hop count and load performance measures, we introduce the new notion of virtual channel distance, that estimates the time needed to reconstruct a virtual channel during a handover phase. In order to make the rerouting phase imperceptible to users and thus to obtain a sufficient QoS, the maximum distance between two virtual channels must be maintained as low as possible. Therefore, a natural combinatorial problem arises in which suitable trade-offs must be determined between the different performance measures.

The paper is organized as follows. In the next section we introduce the model, the notation and the necessary definitions. In Section 3 we provide hardness results for the layout construction problem. In Section 4 and 5 we provide optimal layouts for chains and rings, respectively. Finally, in Section 6, we give some conclusive remarks and discuss some open questions.

2 The WATM Model

We model the network as an undirected graph $G = (V, E)$, where nodes in V represent switches and edges in E are point-to-point communication links. In G there exists a subset of nodes $U \subseteq V$ constituted by cells with corresponding radio stations, i.e., switches adapted to support mobility and having the additional capability of establishing connections with the mobile terminals. A distinguished source node $s \in V$ provides high speed services to the users moving along the network. We observe that, according to the wireless nature of the system, during the handover phase mobile terminals do not necessarily have to move along the network G, but they can switch directly from one cell to another, provided that they are adjacent in the physical space. It is thus possible to define a (connected) adjacency graph $A = (U, F)$, whose edges in F represent adjacencies between cells.

A *layout* Ψ for $G = (V, E)$ with source $s \in V$ is a collection of paths in G, termed *virtual paths* (VPs for short), and a mapping that defines, for each cell $u \in U$, a virtual channel $VC_\Psi(u)$ connecting s to u, i.e., a collection of VPs whose concatenation forms a shortest path in G from s to u.

Definition 1. *[12] The* hop count *$h_\Psi(u)$ of a node $u \in U$ in a layout Ψ is the number of VPs contained in $VC_\Psi(u)$, that is $|VC_\Psi(u)|$. The* maximal hop count *of Ψ is $\mathcal{H}_{\max}(\Psi) \equiv \max_{u \in U}\{h_\Psi(u)\}$.*

Definition 2. *[12] The* load *$l_\Psi(e)$ of an edge $e \in E$ in a layout Ψ is the number of VPs $\psi \in \Psi$ that include e. The* maximal load *$\mathcal{L}_{\max}(\Psi)$ of Ψ is $\max_{e \in E}\{l_\Psi(e)\}$.*

As already observed, when passing from a cell $u \in U$ to an adjacent one $v \in U$, the virtual channel $VC_\Psi(v)$ must be reconstructed from $VC_\Psi(u)$ changing only a limited number of VPs. Once fixed $VC_\Psi(u)$ and $VC_\Psi(v)$, denoted as $VC_\Psi(u, v)$ the set of VPs in the subchannel given by the longest common prefix of $VC_\Psi(u)$ and $VC_\Psi(v)$, this requires the deletion of all the VPs of $VC_\Psi(u)$ that occur after $VC_\Psi(u, v)$, plus the addition of all the VPs of $VC_\Psi(v)$ after $VC_\Psi(u, v)$. The number of removed and added VPs, denoted as $D(VC_\Psi(u), VC_\Psi(v))$, is called the distance of $VC_\Psi(u)$ and $VC_\Psi(v)$ and naturally defines a channel distance measure d_Ψ between pairs of adjacent nodes in A.

Definition 3. *The channel* distance *of two nodes u and v such that $\{u, v\} \in F$ (i.e., adjacent in A) is $d_\Psi(u, v) = D(VC_\Psi(u), VC_\Psi(v)) = h_\Psi(u) + h_\Psi(v) - 2|VC_\Psi(u, v)|$. The* maximal distance *of Ψ is $\mathcal{D}_{\max}(\Psi) \equiv \max_{\{u,v\} \in F}\{d_\Psi(u, v)\}$.*

It is now possible to give the following definition on WATM layouts.

Definition 4. *A layout Ψ with $\mathcal{H}_{\max}(\Psi) \leq h$, $\mathcal{L}_{\max}(\Psi) \leq l$ and $\mathcal{D}_{\max}(\Psi) \leq d$ is a $\langle h, l, d\rangle$-*layout *for G, s and A.*

In the following, when the layout Ψ is clear from the context, for simplicity we will drop the index Ψ from the notation. Moreover, we will always assume that all the VPs of Ψ are contained in at least one VC. In fact, if such property does not hold, the unused VPs can be simply removed without increasing the performance measures h, l and d.

3 Hardness of Construction

In this section we show that constructing optimal dynamic layouts is in general an NP-hard problem, even for the very simple case $h = 2$ and $l = d = 1$.

Notice that when $d = 1$, for any two cells $u, v \in U$ adjacent in $A = (U, F)$, during an handover from u to v by definition only one VP can be modified. This means that in every $\langle h, l, 1\rangle$-layout Ψ, either $VC(v)$ is a prefix of $VC(u)$ and thus $VC(v)$ is obtained from $VC(u)$ by adding a new VP from u to v, or vice versa. In any case, a VP between u and v must be contained in Ψ. As a direct consequence, the virtual topology defined by the VPs of Ψ coincides with the adjacency graph A.

Theorem 1. *Given a network $G = (V, E)$, a source $s \in V$ and an adjacency graph $A = (U, F)$, deciding the existence of a $\langle 2, 1, 1\rangle$-layout for G, s and A is an NP-complete problem.*

For $h = 1$, any l and any d, the layout construction problem can be solved in polynomial time by exploiting suitable flow constrictions like the ones presented in [9].

4 Optimal Layouts for Chain Networks

In this section we provide optimal layouts for chain networks. More precisely, we consider the case in which the physical graph is a chain C_n of n nodes, that is $V = \{1, 2, \ldots, n\}$ and $E = \{\{v, v + 1\} | 1 \leq v \leq n - 1\}$, and the adjacency graph A coincides with C_n. Moreover, without loss of generality, we take the leftmost node of the chain as the source, i.e. $s = 1$, as otherwise we can split the layout construction problem into two equivalent independent subproblems for the left and the right hand sides of the source, respectively. Finally, we always assume $d > 1$, as by the same considerations of the previous section the virtual topology induced by the VPs of any $\langle h, l, 1\rangle$-layout Ψ coincides with the adjacency graph A and thus with C_n. Therefore, the largest chain admitting a $\langle h, l, 1\rangle$-layout is such that $n = h + 1$.

In the following we denote by $\langle u, v\rangle$ the unique VP corresponding to the shortest path from u to v in C_n and by $\langle\langle s, v_1\rangle\langle v_1, v_2\rangle \ldots \langle v_k, v\rangle\rangle$ or simply $\langle s, v_1, v_2, \ldots, v_k, v\rangle$ the virtual channel $VC(v)$ of v given by the concatenation of the VPs $\langle s, v_1\rangle$, $\langle v_1, v_2\rangle$, ..., $\langle v_k, v\rangle$. Clearly, $s < v_1 < v_2 < \ldots < v_k < v$.

Definition 5. *Two VPs $\langle u_1, v_1\rangle$ and $\langle u_2, v_2\rangle$ are crossing if $u_1 < u_2 < v_1 < v_2$. A layout Ψ is* crossing-free *if it does not contain any pair of crossing VPs.*

Definition 6. *A layout Ψ is canonic if it is crossing-free and the virtual topology induced by its VPs is a tree.*

According to the following definition, a $\langle h, l, d\rangle$-layout for chains is optimal if it reaches the maximum number of nodes.

Definition 7. *Given fixed h,l,d and a $\langle h, l, d\rangle$-layout Ψ for a chain C_n, Ψ is optimal if no $\langle h, l, d\rangle$-layout exists for any chain C_m with $m > n$.*

We now prove that for every h,l,d, the determination of an optimal $\langle h, l, d\rangle$-layout can be restricted to the class of the canonic layouts.

Theorem 2. *For every h, l, d, any optimal $\langle h, l, d\rangle$-layout for a chain is canonic.*

Motivated by Theorem 2, in the remaining part of this section we focus on canonic $\langle h, l, d\rangle$-layouts for chains, as they can be the only optimal ones.

Let us say that a tree is ordered if it is rooted and for every internal node a total order is defined on its children. As shown in [12], an ordered tree induces in a natural way a canonic layout and vice versa.

Therefore, there exists a bijection between canonic layouts and ordered trees.

We now introduce a new class of ordered trees $\mathcal{T}(h, l, d)$ that allows to completely define the structure of an optimal $\langle h, l, d\rangle$-layout. Informally, denoted as $\mathcal{T}(h, l)$ the ordered tree corresponding to optimal layouts with maximum hop count h and load l without considering the distance measure [11], $\mathcal{T}(h, l, d)$ is a maximal subtree of $\mathcal{T}(h, l)$ with the additional property that the distance between two adjacent nodes in the preorder labelling of the ordered tree, and thus between two adjacent nodes in the induced layout, is always at most d. Moreover, the containment of $\mathcal{T}(h, l, d)$ in $\mathcal{T}(h, l)$ guarantees that the hop count h and the load l are not exceeded in the induced layout.

The definition of $\mathcal{T}(h, l, d)$ is recursive and the solution of the associated recurrence gives the exact number of the nodes reached by an optimal $\langle h, l, d\rangle$-layout. Before introducing $\mathcal{T}(h, l, d)$, let us define another ordered tree that is exploited in its definition.

Definition 8. *Given any h, l, d, $T(h, l, d)$ is an ordered tree defined recursively as follows. $T(h, l, d)$ is obtained by joining the roots of $min\{h, d-1\}$ subtrees $T(i, l-1, d)$ with $h - min\{h, d-1\} + 1 < i \leq h$ in such a way that the root of $T(i-1, l-1, d)$ is the rightmost child of the root of $T(i, l-1, d)$. A last node is finally added as the rightmost child of $T(h - min\{h, d-1\} + 1, l-1, d)$. Trees $T(0, l, d)$ and $T(h, 0, d)$ consist of a unique node.*

Definition 9. *The ordered tree $\mathcal{T}(h, l, d)$ is defined recursively as the join of the roots of the tree $\mathcal{T}(h-1, l, d)$ and the tree $T(h, l-1, d)$ in such a way that the root of $\mathcal{T}(h-1, l, d)$ is the rightmost child of the root of $T(h, l-1, d)$. Trees $\mathcal{T}(0, l, d)$ and $\mathcal{T}(h, 0, d)$ consist of a unique node.*

The following lemma establishes that $\mathcal{T}(h, l, d)$ is the ordered tree induced by an optimal $\langle h, l, d\rangle$-layout.

Lemma 1. *The layout Ψ induced by $\mathcal{T}(h,l,d)$ is a $\langle h,l,d\rangle$-layout. Moreover, every canonic $\langle h,l,d\rangle$-layout Ψ induces an ordered subtree of $\mathcal{T}(h,l,d)$.*

Let $\mathcal{T}_n(h,l,d)$ and $T_n(h,l,d)$ denote the number of nodes in $\mathcal{T}(h,l,d)$ and in $T(h,l,d)$, respectively. Directly from Definition 8 and 9, it follows that $\mathcal{T}_n(h,l,d) = T_n(h,l-1,d) + \mathcal{T}_n(h-1,l,d) = \sum_{k=0}^{h} T_n(k,l-1,d)$, where the value of every $T_n(k,l-1,d)$ for $0 \leq k \leq h$ is obtained by the following recursive equation:

$$T_n(h,l,d) = \begin{cases} 1 & \text{if } l = 0 \text{ or } h = 0, \\ 1 + \sum_{j=0}^{min\{h,d-1\}-1} T_n(h-j,l-1,d) & \text{otherwise.} \end{cases}$$

Before solving the above recurrence, we recall that given $n+1$ positive integers $m, k_1, \ldots, k_n$ such that $m = k_1 + \cdots + k_n$, the multinomial coefficient $\binom{m}{k_1,\ldots,k_n}$ is defined as $\frac{m!}{k_1! \cdot k_2! \cdot \cdots \cdot k_n!}$.

Lemma 2. *For every h,l,d, $T_n(h,l,d) =$*

$$\sum_{i=0}^{l} \sum_{j=0}^{h-1} \sum_{\substack{0 \leq k_{d-2} \leq k_{d-3} \leq \ldots \leq k_2 \leq k_1 \leq i \\ k_1 + k_2 + \ldots + k_{d-2} = j}} \binom{i}{i-k_1, k_1-k_2, \ldots, k_{d-3}-k_{d-2}, k_{d-2}}.$$

The following theorem is a direct consequence of Lemma 1, Lemma 2 and Definition 9.

Theorem 3. *For every h,l,d, the maximum number of nodes reachable on a chain network by a $\langle h,l,d\rangle$-layout is $\mathcal{T}_n(h,l,d) = 1 + \sum_{k=1}^{h} T_n(k,l-1,d)$.*

More details will be shown in the full version of the paper.

5 Optimal Layouts for Ring Networks

In this section we provide optimal layouts for ring networks R_n with $V = \{0,1,\ldots,n-1\}$ and $E = \{\{i,(i+1)\,mod\,n\} | 0 \leq i \leq n-1\}$. Again we assume that the adjacency graph A coincides with R_n and without loss of generality we take $s = 0$ as the source node. Moreover, we let $d > 1$, since as remarked in Section 3, no layout with maximum distance 1 exists for cyclic adjacency graphs.

Notice that in any $\langle h,l,d\rangle$-layout Ψ for R_n, by the shortest path property, if n is odd the nodes in the subring $[1, \lfloor \frac{n}{2} \rfloor]$ are reached in one direction from the source, say clockwise, while all the remaining ones anti-clockwise. This means that Ψ can be divided into two separated sublayouts Ψ_c and Ψ_a respectively for the subchains of the nodes reached clockwise in Ψ, that is $[0, \lfloor \frac{n}{2} \rfloor]$, and anticlockwise, that is from $\lceil \frac{n}{2} \rceil$ to 0 in clockwise direction, extremes included. However, the results of the previous section for chains do not extend in a trivial way, as a further constraint exists for the final nodes $\lfloor \frac{n}{2} \rfloor$ and $\lceil \frac{n}{2} \rceil$, that are adjacent in A and thus must be at distance at most d in Ψ. A similar observation holds when n is even.

As for chains, let us say that a $\langle h, l, d\rangle$-layout Ψ for rings is optimal if it reaches the maximum number of nodes. Moreover, let us call Ψ canonic if the clockwise and anticlockwise sublayouts Ψ_c and Ψ_a are both crossing-free and the virtual topologies induced by their VPs are trees. The following lemma is the equivalent of Theorem 2 for rings.

Lemma 3. *For every h, l, d, there exists an optimal $\langle h, l, d\rangle$-layout for rings that is canonic.*

Starting from Lemma 3, we generalize the ordered tree $\mathcal{T}(h, l, d)$ to $\mathcal{T}(h, l, d, t)$ by adding a further parameter $t \leq h$, which fixes the hop count of the rightmost leaf to t. Roughly speaking, $\mathcal{T}(h, l, d, h) = \mathcal{T}(h, l, d)$ and $\mathcal{T}(h, l, d, d-1) = T(h, l, d)$. More precisely, $\mathcal{T}(h, l, d, t)$ is defined recursively as the join of the roots of $min\{h, t\}$ subtrees $T(i, l-1, d)$ for $h - min\{h, t\} < i \leq h$ in such a way that for $i < h$ the root of a $T(i, l-1, d)$ is the rightmost child of the root of a $T(i+1, l-1, d)$, plus a final node as rightmost child of $T(h-min\{h, t\}+1, l-1, d)$. Thus, $\mathcal{T}_n(h, l, d, t) = 1 + \sum_{k=h-min\{h,t\}+1}^{h} T_n(k, l-1, d)$

Lemma 1 extends directly to $\mathcal{T}(h, l, d, t)$, that in turn corresponds to an optimal $\langle h, l, d\rangle$-layout for a chain with the further property that the rightmost node (opposite of the source) has hop count t. Therefore, it is possible to prove the following theorem.

Theorem 4. *The maximum number of nodes reachable on a ring network by a $\langle h, l, d\rangle$-layout is $2\mathcal{T}_n(h, l, d, \lfloor \frac{d}{2} \rfloor) - ((d+1) \ mod \ 2)$, with $\mathcal{T}_n(h, l, d, \lfloor \frac{d}{2} \rfloor) = 1 + \sum_{k=h-min\{h, \lfloor \frac{d}{2} \rfloor\}+1}^{h} T_n(k, l-1, d)$.*

6 Conclusion

We have extended the basic ATM model presented in [12,7] to cope with QoS and mobility aspect in wireless ATM networks. This is obtained by adding a further measure, the VCs distance, that represents the time needed to reconstruct connecting VCs when handovers occur and must be maintained as low as possible in order to avoid the rerouting mechanism to be appreciated by the mobile users. We have shown that finding suitable trade-offs between the various performance measures is in general an intractable problem, while optimal constructions have been given for chain and ring topologies.

Among the various questions left open, we have the extension of our results to more general topologies. Moreover, another worth investigating issue is the determination of layouts in which the routed paths are not necessarily the shortest ones, but have a fixed stretch factor or even unbounded length. Finally, all the results should be extended to other communication patterns like all-to-all.

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