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Wireless LANs: From WarChalking to Open Access Networks*

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Abstract. This work discusses the evolution of W-LANs from their current status of wireless termination of LAN services to a possible global infrastructure where the access networks become open to multiple operators and a vehicle of a win-win scenario, where both users and operators benefit from the new network architecture. The idea of Open Access Networks (OANs) can go beyond wireless HotSpots and be generalized to a generic shared access infrastructure that fosters service operators competition and drastically reduces the cost of last mile coverage.

The general concept of Open Access Networks is detailed, highlighting its difference with the more traditional model of vertical integration of the access network into the global service. About the OANs development, it is shown how to support the quick and smooth evolution of the infrastructure toward a widespread and reliable communication support.

Business models are discussed by mentioning the different actors, the market organization and the different organization forms.

The final part of the paper is devoted to technical challenges such as access control, security, privacy, roaming, resource exploitation and service differentiation. As an example of how to tackle these problems, we discuss a pricing technique devoted to resource management and billing support.

In addition we present a simulation on how the OAN concept can speed-up the deployment of broadband access in a real case.

Keywords:

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1. History & perspective

The telecommunication market has suffered in the past from a syndrome we can epitomize as "*the network is the service*," deriving from the monolithic structure of the early telephone networks. Conceptual efforts to overcome this syndrome date back to the '70s, with the development of the ISDN (Integrated Services Digital Network) paradigm that introduced the idea of *value added services*, i.e., services built on top of another, more basilar service, generally a transport service.

Thirty years have passed, Mobile Telephony (especially GSM) and the Internet have shaken the foundations of telecommunications, but still revenues derive almost entirely from connectivity and traffic volume. Most existing networks are owned by operators that compete with each other at all levels and do not offer local roaming to end-users (e.g., no GSM operator allows its customers to use alternative operators in their home area and most wired broadband providers make it as hard as they can for end-users to change provider). The result is high cost of services and barriers for competition.

The main reason for the actual situation is the vertical integration of networks. The same company owns or controls the whole service stack, from the hardware infrastructure to the information-brokering or content-delivery. From the technical point of view the need for a layered infrastructure (see both the TCP/IP and ISO/OSI models) was recognized as a key factor for development, but the idea has not percolated to the business organization.

The vertical integration has several drawbacks. First of all, it introduces dependencies between different levels that limit innovation, because the introduction of a new service may require the upgrade of the whole structure: the growing problems of UMTS are a good example.

Second, it hampers competition. Real competition stems either from technological innovation at the hardware level (think about the introduction of LANs), or from the invention of new services (think about the Web or SMS). In both cases, a vertically integrated network implies that a new, competitive idea, can enter the market only with a '*new network*', i.e., with an upgrade of the whole infrastructure, which is extremely expensive.

Last but not least, vertical integration reduces statistical sharing of resources, which means that the average service cost is higher.

Following the global crisis of the telecommunication market, two major technical/economic tasks have emerged: (i) the real bandwidth bottleneck is the access network, while modern value-added services require response times that are not compatible with low-bandwidth access; (ii) bandwidth-hungry mobile users tend to be nomadic (they move from one place to another and then require service) rather than fast moving, as 2G/3G networks assumed. Both problems are related with access networks, but the costs associated with the

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deployment of new access networks are high, bringing operators to a stall.

Once again we are stuck with the problem of vertical integration. New services are likely to be available, but they require new access networks: innovative operators cannot afford the cost, while incumbent operators do not see any strategic advantage in the investment.

Some problems can be solved by providing physical access networks shared by multiple operators: an Open Access Network (OAN). The result will be freedom of choice for users, freedom of service development for providers, and lower costs for deployment and usage. This win-win scenario leads to a wider coverage both in terms of physical area and number of users connecting to this open marketplace.

One of the goals of OANs is to share investments among all interested actors, which are not only telecom operators. Because the new networks will have higher capacity and better quality, the customer base will increase, and even the incumbent operators are likely to join OANs. At the same time, geographically based consortia or entities (e.g., housing corporations, tourist organizations, municipalities, etc.) have all the advantage in promoting the diffusion of OANs on the territory, because their diffusion means a better global competitive position of the area. Therefore they might also choose to share the costs of deployment.

The widespread diffusion of W-LANs and community networks is a first step toward OANs and they might represent a key factor in changing the game rules. W-LANs are a relative novelty and curiosity fosters innovation. W-LANs offer a mixture of the two "technologies" (Internet and mobile communications) that have most impressed the non-technical community in the last decade or so, thus they represent a logical evolution in customers views. W-LANs are relatively cheap and offer a natural way of sharing resources. For all these reasons, in this paper we focus mainly on W-LANs, though it is clear that the OAN concept applies to almost any access network technique.

2. Open access networks

Although the idea of sharing a common infrastructure to provide competitive communication services may be perceived as revolutionary in the telecommunication context, it is widely exploited in other areas, such as road systems: who could imagine the use of different sets of roads to separate traffic from different transportation companies? The challenge to get the infrastructure-sharing concept accepted in the telecommunication area is to design a natural architecture for open communication [14], as well as a clear set of usage and trust rules. This means that users and their agents, OAN-operators and service providers must build commercial relationships with the possibility of mutual control, which is the only way trust can be attained.

As suggested in the title, an early implementation of an OAN concept based on W-LANs exploited the (mis)use of private W-LAN access to the Internet, often without permission of the owner (WarChalking). Clearly the OAN concept has nothing to do with the misuse of resources and it is more complex than simply sharing a wireless connection to the Internet. Indeed, the OAN concept is not constrained to wireless networks at all and requires a management infrastructure in addition to access points to be implemented. W-LANs simply offer a natural context to introduce OANs.

2.1. Pilots

Pilot networks providing proof of concept to widen the access network bottleneck by using shared network elements are already in operation.

A pioneering effort was made in StockholmOpen.net [15], the first pilot in what has become the www.swedenopen.net program. It exploits experiences from a department-neutral campus network [8,16], developed at the IT-university in Stockholm, a joint venture between KTH and Stockholm University. A selection server was developed to let users select the service provider they want to use to connect to the Internet [10]. Different users connecting via the same access network can use different service providers.

The StockholmOpen.net access consists of a shared city-wide link level network, together with rules allowing anyone to attach access points and allowing every operator to connect a gateway to authenticate its users and provide services via the OAN.

The shared backbone in StockholmOpen.net is a 150 km dark fiber with 1 Gbit/s core switches and 100 Mbit/s distribution switches. It includes both wired (10/100 Mbit/s Ethernet) and wireless (IEEE 802.11b) access points. The wired access points are deployed in homes while the wireless access points are located in public places where nomadic users dwell, such as the City Hall, the house of culture, shopping malls and academic as well as industrial campuses. To date, there are 144 fixed and 83 wireless access points. More than 1440 users (MAC addresses) have been registered. There are currently four public and one private service provider for the users to choose from. More service providers are in the process of connecting and more users have expressed an interest in getting their areas connected to the shared network.

Other pilots based on the StockholmOpen.net ideas and technology are currently in operation in Nora and SkellefteåR in Sweden, Turku in Finland, Barcelona in Spain, and Maputo in Mozambique. The software is distributed from software.stockholmopen.net as open source and has been downloaded from a large number of sites.

Other pilots based on similar concepts exist. One of them is being built in Italy in Trento [3,22]. The focus of this project is principally on wireless hot spots to serve nomadic users, and targeted problems are mainly related with distributed authentication, roaming, pricing and billing issues.

Another example is the NoCat [2] wireless community network in Sonoma, CA, that also distributes open source code for authentication and other purposes. Many other wireless community networks exist, often sponsored by municipalities like for examples in Seattle [18] and Toronto [23] (a longer list can be found in [1]). See also [9] for a book on the subject.

Among the lessons learned from the first generation of pilots, there are technology, management and business aspects. To make open access networks scalable, flexible and secure, technical research and development is needed in a number of areas, including issues in networking, a wide range of security aspects, advanced services and applications, business models and usage-oriented interfaces. Some of these issues are discussed later in this paper.

From a management point of view the main issues include who should own, operate and maintain an operator neutral access network [11]. From a business point of view, there are two main user basins: the home sector and nomadic users. Nomadic users are still limited today, but they are increasing very fast and recent EU directives on the subject hint at a shared use or resources.

A key issue to get the concept accepted as a commercially viable network architecture is the establishment of a trusted actor that owns, maintains and supervises a well-designed set of access rules to a common shared infrastructure, thus creating a marketplace for users and a wide spectrum of service providers [13].

The second generation pilots in the Open.net framework are now being planned. All kinds of actors are involved in the requirement specification phase: users, OAN operators and service providers. The discussion has spread over the world. In the Nordic and Baltic countries, some 20 pilots are being discussed, international development cooperation agencies are discussing projects based on the open.net concept in countries in Africa, Asia and America.

An enabling factor is the growing number of networks owned by actors that are neutral in their relation to the service. Examples of such actors are real estate owners, companies, universities, schools, cities, municipalities, airports, shopping malls, sport arenas, hotels, conference sites, etc. Many of these actors have reasons for providing access to their users, customers, tenants, students, employees, inhabitants, . . .

Another enabling factor is the fact that anyone that sees an economic opportunity can act. If the business models of available operators do not give you a last mile network connection, or a local monopoly make prices too high, you can deploy a first mile connection yourself, to take your own access point to the closest point of presence of the service providers you would like to use. This possibility opens up opportunities, especially for people living in rural areas and developing countries who can exploit local economic opportunities that global national business models of large operators cannot consider.

The industrialization of open access networks involves establishing new actors and new business models. Business models used today are based on the vertical integration of communication services and networks and are centered on operators controlling the value chain. OANs require fundamentally different business models based on value provisioning to all involved actors. W-LANs offer the perfect medium for distributing telecommunication services with a shared and cost-effective access network. The present technology may be suitable for some services only, but future evolutions will certainly allow a larger array of services to be effectively offered.

3. Business model

The definition of the architecture of a new system implies correct identifying and outlining the technical, social and economic viability of the system. We discuss here and in Section 4 mainly social and economic aspects, while we discuss some technical aspects in Section 5. Section 6 is entirely devoted to pricing.

3.1. Market segmentation

The telecom market has been traditionally subdivided in business and private. This subdivision should reflect different needs, different budgets and different expected quality.

This dichotomy, however, does not reflect the modern, multifaceted telecommunication offerings. One example are mobile communications (GSM/GPRS): the network and service are *identical* for any customer, just the pricing scheme varies, so that quite often business clients go for private contracts. Substitution effects like arbitrage (buying a service, repackaging and reselling it) or traffic splitting are common ways to defeat versioning in the telecom market. Indeed, in GSM/GPRS the difficult mapping of needs onto the technical management of the network can lead to absurd situations. For instance the strict precedence given to voice (GSM) over packet data (GPRS) can prevent a business client from sending a very important message because of an ongoing futile chat.

The business/private scheme is problematic for several reasons, the first of which is the complexity of telecommunication services. A market segmentation scheme that is perfect for fixed telephony does not apply to mobile telephony and may well not make any sense for the Internet. For instance, large bandwidth access is not necessarily more appealing for business than for families, because entertainment applications are bandwidth-hungry. Conversely, a multicast enabled infrastructure can be a requirement in business for videoconferencing, and might not be of interest at all for private users.

The market segmentation addressed by OANs is transversal, covering both business and family users. Three main areas, with different needs and requirements can be envisaged.

3.1.1. Home access

Homes are the private customers primary venue for network access. Families are attentive to prices and have extremely varied needs, so that many different content and service providers can be involved in the build-up of services. The result is that residential areas are a natural target for the build-out of open access networks. The smooth incremental nature of OANs deployment, with the low initial cost of W-LAN infrastructures, can trigger positive feedback loops, since a small initial investment enables a large number of services for a large number of people. While more services are deployed and more users join the services, the OAN can be upgraded, while cost sharing keeps service prices low.

3.1.2. SOHO customers

Small enterprises share the price elasticity with family market and, similarly, represent a volume market, where the introduction of services is often blocked by the initial investment. The services offered through the OAN may be different from the services offered to families, but, to a large extent, the distribution infrastructure can be shared between family market and SOHO market. If not for other reasons, the sharing can be based on largely non-overlapping peak usage hours.

In such a mixed scenario, however, efficient pricing schemes (not necessarily related to money) must be deployed to enforce proper QoS guarantees. One such scheme is presented in Section 6.

3.1.3. Hot Spots

Access at public places is possibly the "hottest topic", when discussing the introduction of 802.11 based access networks. Today, Hot Spot access to the Internet is a much smaller market than any other telecom sector, but just thinking at the mobile telephony market explains why opinions on this subject are strong and rarely objective.

The Hot Spot deployment and the services offering therein, is the place where ends meet: home users would like access as if they were at home, SOHO customers too, but, most of all, also large corporations are interested in their employees receiving service while outside corporate premises. This means that Hot Spots are the most interesting, but also the most difficult market share, since different Hot Spots can have very different service and traffic requirements.

In some places, such as airports and train stations, the broadband access can be a "natural" profitable business even with a traditional approach of vertical service integration. However, at the majority of public places suggested for public broadband access, such as cafés, restaurants, museums, etc., the demand is varied and, today, it is still very low, as well as customers willingness to pay a high price.

In all cases, broadband access at public places is a very good way to enhance the overall access service by adding the possibility for ubiquitous access. For this to happen, however, using the same provider and account used at home or in office is a key requirement and OANs offer a natural way for such provisioning.

3.2. Service model

The proposed business model includes a number of logical entities we call actors, that cooperate to build the overall infrastructure. We outline here the roles of the different actors, keeping in mind that minor differences may arise based on different implementations. Though we detail many actors, the basic idea is depicted in figure 1 and includes only three main actors: users (U), the OAN, and the service providers (SP).

The OAN is generally unique, because its success is based on cost reduction through resource sharing. Users and service

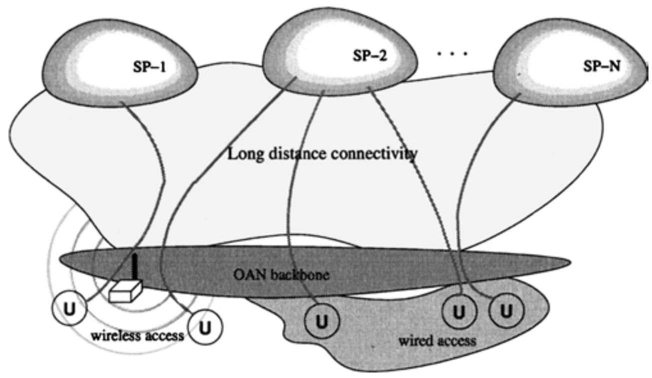

Figure 1. Basic logical structure of an OAN based telecommunication service, the OAN supports any SP and any authorized user through wired or wireless access.

providers are instead a multiplicity. SPs in particular can either be competitors or offer different services. Notice that the uniqueness of the OAN is more conceptual than real. First of all, it is location based, in the sense that there can (and will) be different OANs in different places. Moreover, in areas with high potential revenues, like city centers, there is nothing preventing the presence of different OANs giving access to different communities. Indeed, this can be a vehicle of technological upgrade, since competing OANs will seek for the best possible technology to offer the best support to services.

As highlighted in figure 1, the OAN acts basically as an intermediator between SPs and users. As an intermediator it must not introduce distortions of the market, hence it must adhere to the following two sets of rules, that define and *open* and *neutral* network.

Rule set $\mathcal{R}^o$: In an *open* network.

- r_1^o: Any user must be free to select any service provider on the OAN;
- r_2^o: Any service provider must be free to deliver services over the OAN to any user;
- r_3^o: Anyone should be allowed to add access points to the OAN and anyone should be allowed to extend the shared part of the OAN.

Rule set $\mathcal{R}^n$—In a *neutral* network.

- r_1^n: SPs should be offered transport (or bearer) services at different architectural levels and refinements, so that different services and different providers can find their natural place in the OAN;
- r_2^n: All SPs must be offered the same conditions;
- r_3^n: There can be no disloyal competition, and the owner (or operator) of the OAN is not allowed to offer services to end users.

The heuristic behind rule set $\mathcal{R}^o$ is the definition of an infrastructure that is free of growing with needs. The meaning of rule r_3^o can be a little obscure, but it is this rule that ensures that any user can be reached by services. The meaning of rule set $\mathcal{R}^n$ is instead the definition of a fair playground for competition. We incidentally notice that EU legislation is moving toward a situation as described by rule set $\mathcal{R}^n$, though the path is erratic and harshly opposed by incumbent telephone operators (both fixed and mobile). In particular rule r_3^n is generally not stated explicitly and is more often expressed in a mild way under the term of "free roaming access." However, the history of twisted pair liberalization (or unbundling) shows that the owner of the physical infrastructure has always a lead on other service providers simply because it can adjust the cost sharing between the physical infrastructure and the service provisioning.

3.2.1. End users and user agents

End users or simply users are customers of the telecommunication services, but they can also deploy and establish part of the hardware infrastructure, such as in-building cables.

We use the term "user agent" to denote any organization that acts on behalf of a group of end users in establishing access networks, connects these networks to the open access infrastructure and thereby provides the user group a possibility to access telecommunication services via a connected service provider. Examples of user agents include housing companies that establish real estate networks and connect them to the OAN. Another example, can be the municipality that decides to provide the basic telecommunication infrastructure as a part of the urbanization process, just like sewage, water or electricity.

Several users or user agents can join and possibly form an economic society both for the maintenance of the infrastructure or to share additional access costs, e.g., the cost of ducts and fiber to reach several suburbs or villages. Indeed, cooperatives are a good example worldwide of such economic societies, and in Europe there are examples of cooperative public infrastructure management that dates back centuries and still provide high level management services.

3.2.2. The Open.Net organization

The central part of the model is the organization responsible for setting – and enforcing – the rules for the use of the OAN. To a given extent this organization is the OAN itself, and it is of the paramount importance that it is defined correctly, avoiding the danger that the OAN itself becomes a bottleneck of the infrastructure.

We argue that Open.Net organizations should be nonprofit, since in many cases the OAN is unique and hence a monopoly, which is contrary to the openness concept.

The main mission of Open.Nets is the strategic management of the infrastructure, which means that their key role is the implementation of the rule sets $\mathcal{R}^o$ and $\mathcal{R}^n$.

This scenario is extremely flexible, since it allows exploiting different development opportunities. For instance the Open.Net of a metropolitan area can rent dark fibers laid by the different municipalities as urbanizing effort, own the active devices for traffic and network management, outsource their maintenance, and finally use the Access Points "offered" by users and user agents in exchange for the basic connectivity service.

3.2.3. Service provider

The service providers are all the economical subjects that offer value added services or simply long distance telecom services. If the standard Internet access service is considered, they are simply ISP (Internet Service Providers). However, they may well offer new and alternative services, such as video on demand, or access to any specific "closed community network" supporting a special interest group.

3.3. Commercial relationships

Traditional commercial models (not only in communications) provide only two actors: the buyer and the seller. Exceptions to this basic rule started to show up in tertiary (service-based) markets, where intermediate agents (or brokers) simplify the interaction of buyer and seller. Examples include tourist operators and, in the telecom market, U.S. local telephone companies that act as brokers between users and long-haul operators.

A three-actor scenario is surely more complex than a two-actor one, besides the OAN model envisages *clusters* of dynamic actors, creating commercial relationships on the fly and not simply between a seller, a buyer and the OAN as broker.

Indeed, two different scenarios can be envisaged. In the first one, users pay separately the OAN (through the Open.Net organization) and the SPs. In the second one, users only have commercial contracts with the SPs, and the SPs have commercial contracts with the Open.Net organizations and pay them the right of access providing support for the OAN maintenance, operation and upgrade. The first one makes it very difficult to support mobility and roaming, thus we only consider the second one.

End-users are billed by service providers that in turn pay a share of their revenue to the Open.Net Organization. In many cases revenues don't even need to cover the whole costs, for instance real estate owners may consider the real estate W-LAN as an investment that increases the value of the property and thereby cover part or all the network costs through the rent.

Depending on this choice there can be additional commercial relationships and revenue flows that are hidden in this simplified description, but that do not alter the global architecture of the system.

4. Introduction and growth

An infrastructure will only grow if there are sufficient motivations to make the necessary capital investments. Traditionally, operators are those called for infrastructure investment, but this model often slows down new initiatives due to the risk of the large investments. With OAN the initiative of investing in the network infrastructure is shifted toward the users.

The initial introduction of OANs will mostly be based on W-LANs for three main reasons. First, as already noted, they are perfect and inexpensive means for resource sharing. Second, they represent a novelty from the technical and service model point of view (the network where you need it), and novelties are more prone than established technologies to spawn new business. Third, their unlicensed spectrum use calls for a unique, shared infrastructure, rather than multiple infrastructures interfering destructively one another.

4.1. Initial setup

The architecture of an OAN consists of three parts: a backbone network, a number of access networks and access points, and a number of gateways to service provider networks. The backbone connects together the access networks and the gateways. End users attach via wired or wireless access points. Users and user agents connect their access networks and access points to the backbone; service providers attach gateways to the OAN backbone network, either physically or logically. This latter choice has a deep impact on the global network management, with technical implications that are discussed in Section 5.1.

End users select service providers via a service selection mechanism. The traffic to and from the end users is forwarded over the OAN based on the choice of the service provider.

The basic principle of growth in these kinds of networks is based on the extension of the network by establishing and connecting access points to the backbone. In this way the cost of expanding the network is split between the Open.Net organization owning the backbone and the user agents: the Open.Net organization invests in the backbone and the user agents invest in new access networks and their connection to the backbone.

When implementing the above principle, two basic questions arise:

1. Under what conditions does the Open.Net Organization invest in expanding the network to reach new end users?
2. What happens if the Open.Net Organization decides not to invest in extending the backbone network to a certain area and there are potential end users and user agents interested in investing in new access networks in that area?

One possible answer to the first question is the following: The Open.Net Organization will invest in extending the network to a new area if the potential base of new users in that area is large enough to generate a revenue share that can pay back the investment in a reasonable time and with a reasonable associated risk. That is, the decision will be made on commercial grounds (given that no other funding, such as governmental subsidies, is available).

If the cost or the risk of investing to expand the backbone is deemed too high for the Open.Net Organization other models of extending the network are possible. One possibility is through the already cited cooperatives. The basic idea is that user agents, for example a number of housing companies owning apartment buildings in an area, together form an economic society (cooperative) with the purpose to invest in a connection from a point in the area to the backbone. The cost to connect to the established point is carried by each user agent; the cost of the connection from the established point to the backbone is split between the members of the economic society.

4.2. Infrastructure growth

This model enables the growth of the infrastructure in a very simple way. Assume that a number of user agents have established an economic society and a connection to the backbone. Assume also that in a neighboring area, other agents are interested in connecting their access networks to the backbone, but the cost of directly connecting to the backbone is prohibitively high. By joining forces with the already established economic society this can be overcome: the second set of user agents joins the existing economic society, which expands the network to the second area.

Let's observe that this growth model permits to use very different preconditions. For example, if one specific area is entitled to some form of governmental subsidy or support to establish broadband access, this support could be part of the model for one economic society connecting to the backbone, while other economic societies establish connections without such support. With this growth model the initiative to expand the network lies with the users and their agents.

4.2.1. Infrastructure growth simulation

Detailed simulations are being carried out to assess the tecno-economic viability of wireless OANs; we present here preliminary results demonstrating how OANs can speed-up network growth and increase coverage. The simulation considers infrastructure costs only. For example, this scenario can represent a number of public entities interested in offering wireless Internet access.

Nodes (potential users) are distributed around a single point of access to long haul operators or service providers premises. In figure 2, representing the case under study, this point is located at the origin of coordinates in position (0, 0), distance

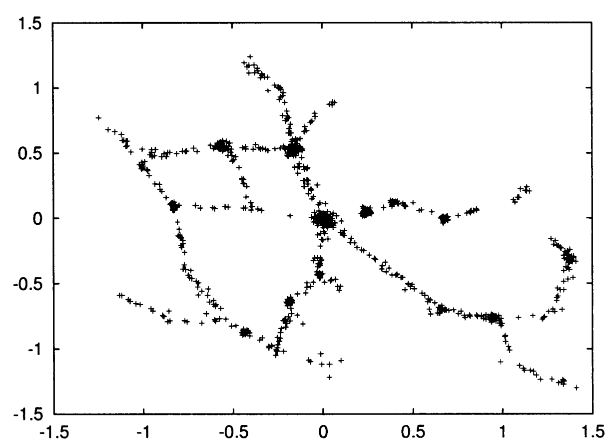

Figure 2. Distribution of users in the simulated network growth.

units are arbitrary. The nodes are arbitrarily distributed around this point that we call "*pivot*;" in figure 2 they follow the population density in Trentino province in north-east Italy. Each node has a bandwidth demand BD_i and 'willingness-to-pay' that increases linearly in time: $v_i t$. The distance between each pair of nodes $d(i, j)$ represents a cost to install the corresponding connection: $cost_{\text{link}}(i, j) = d(i, j)$.

Capital expenses to install infrastructure to connect to the backbone can penalize a minor user. The cost to install a new connection from user i to the backbone access point is given by $cost_{\text{direct}}(i) = cost_{\text{link}}(i, pivot)$. Instead of connecting directly to the pivot point user i may choose to get connection through the OAN network, and to pay only a fraction of the infrastructure cost proportional to his bandwidth consumption. On the other hand, a node which is already connected can offer unused bandwidth and partially recover from his investment cost.

This approach however implies that nodes only cover the part of all infrastructure costs proportional to the actual usage, and the excess is covered by the OAN organization. Therefore, in order to avoid negative profits, we assume that the OAN organization takes an extra charge for connections, proportional to cost with coefficient ϕ.

Explicit expression to calculate cost for a user to connect to OAN through jth node is:

$$cost_{\text{OAN,j}}(i) = \frac{\phi\, BD_i}{link\_capacity}(cost_{\text{link}}(i, j) + cost_{\text{sharing}}(j)),$$

$$cost_{\text{sharing}}(j) = \sum_{k=j}^{\text{pivot}} cost_{\text{link}}(k, uplink(k)),$$

where k goes through the chain of j's uplinks until pivot is reached.

Thus, the OAN price includes cost of all involved links, which is greater than that of a single direct link, and an extra charge. The price can be attractive because it is proportional to the bandwidth usage. In the case considered in our experiments, the OAN organization employs very cautious approach and does not invest in a new connection unless the user's payment covers the expenses; i.e., the condition $cost_{\text{OAN},j}(i) \geq cost_{\text{link}}(i, j)$ must hold.

The user's utility $u = v_i t - cost$ determines the probability that corresponding connection is installed:

$$p = \begin{cases} 0 & \text{if } u \leq 0 \\ u & \text{if } 0 < u < 1 \\ 1 & \text{if } u \geq 1 \end{cases}$$

Figure 3 shows a sample realization of the conducted experiments. It is based on the users distribution depicted in figure 2. Other parameter values are listed in Table 1. All measure units are normalized for generality.

The simulation shows that the OAN can significantly speedup network evolution – the time to connect 90% of the nodes is reduced by more than 50%. Sharing also reduces total infrastructure cost by 70% compared to 'centralized' case, when users can only connect to the backbone directly. This second fact means that the break-even point in investment (i.e., the penetration factor beyond which the business becomes profitable) is smaller in the OAN case, leading to a shorter investment exposure and to lower prices in steady-state. Finally, with the model adopted the OAN organization is secured from negative profits.

Table 1
Values of model parameters.

Parameter	Value
Number of nodes n	1000
Node positions	Accordingly to Trentino province population distribution model
Backbone access position	(0, 0)
Bandwidth demands $d_{bw,i}$	Exponential (1.0)
Link capacity	10.0
v_i	Uniform (0.0, 1.0)
OAN extra charge ϕ factor	1.1

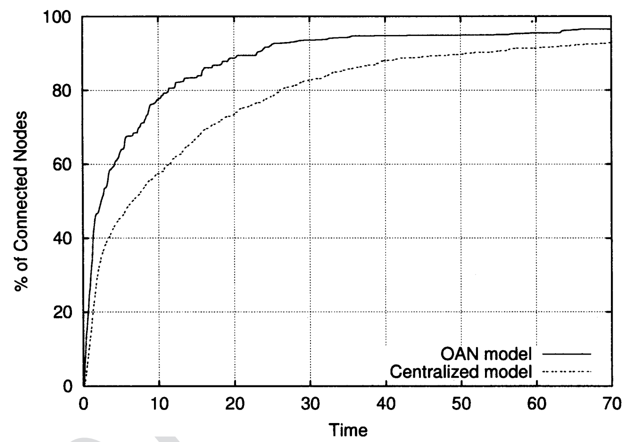

Figure 3. Growth dynamics of OAN compared to centralized model.

5. Technical challenges

While the major frictions on the deployment of OANs are surely commercial and cultural, there are several technical topics that are still open. We discuss here those we deem more important, those we expect will foster important research efforts in the near future; obviously we don't expect to be exhaustive neither in the list nor in the depth of discussion.

5.1. User-providers interaction

The provisioning of transparent support for the interactions of users and service providers is still a challenge that has implications and ties on both security and AAA. We envision two possible solutions: *Local* and *Distributed.* The local solution is currently under experimentation in the StockholmOpen.net project [20], while the distributed one is being experimented within the WILMA project [22].

Since the OAN is not a service provider itself, and does not provide for direct billing and/or reporting to the customers, all the service logic, starting from the authentication down

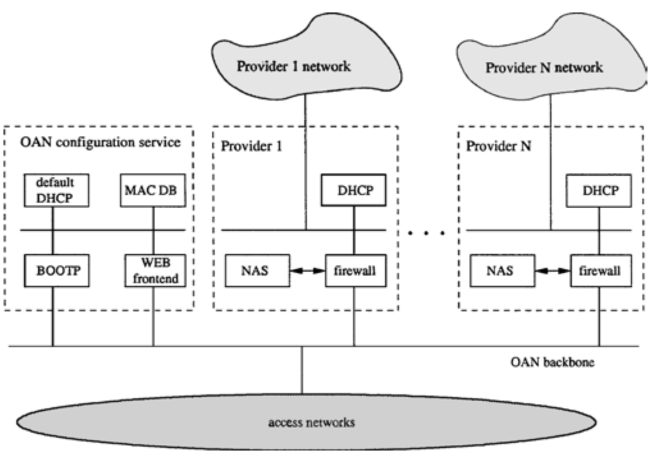

Figure 4. Organization of the *local* user-provider interaction model.

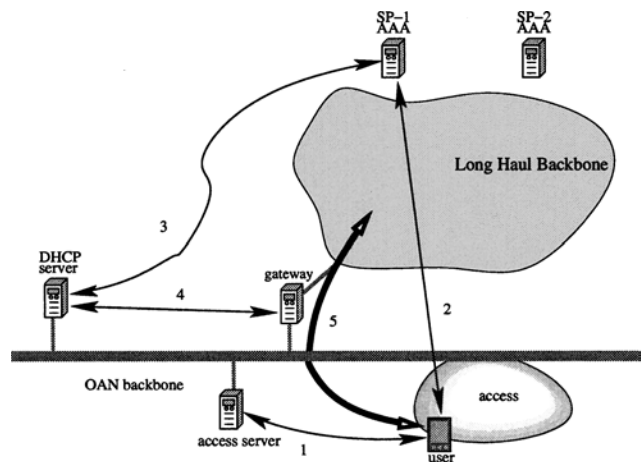

Figure 5. Organization of the *distributed* user-provider interaction model.

to privacy and security problems, must be handled directly between the users and the SPs, with the OANs acting as transparent support.

Figure 4 reports a scheme of the local approach. In this case the OAN operates as a single broadcast domain and new access requests are redirected from an initial OAN access server to a provider specific Network Access Server (NAS) that is physically located on the OAN backbone. The provider specific NAS does all the AAA activities and is also responsible for the correct configuration of the access firewall, while the OAN access server acts only as redirect of the initial request. In practice, the OAN access server offers an initial choice of available providers and, based on the user choice, redirects the request to the selected provider. In practice, each provider may constitute a VLAN [25] on the OAN, so that the redirection and management is fairly simple.

The advantage of this scheme is its extreme simplicity on the OAN side, that has in practice no need of setting up any device on an architectural level higher than a LAN, because everything else, including the IP address is managed by the service provider. On the other hand, it poses some problems as far as scalability is concerned and, most of all, in supporting roaming through different OANs. Roaming is recognized (see for instance [24]) as one of the key services, specially in public HotSpots. With the scheme outlined here a SP that wants to offer service through an OAN has to install devices in the OAN premises, a fact that will prevent SPs to offer services in OANs where they don't expect many customers. Overcoming this problem still requires research and new ideas. One last minor problem is related to the SP change while connected to an OAN. Since the access request is redirected to the SP immediately, there is no trivial means to re-select the provider without disrupting the access connection and setting it up again, with the additional request to notify the OAN to delete the current entry from its local database.

Figure 5 draws the scheme of the distributed approach. This approach assigns some AAA tasks to the OAN and some to the SPs, numbers in the figure represent the sequence of logical information exchange, ending up (5) in the access to the desired service.

The basic idea here is to split user management functionalities between the OAN and the SP. The SP is still in charge of authenticating the user, billing, and all service related procedures. The OAN is instead in charge of managing network level issues, such as DHCP and IP address management.

The main advantage of this approach is that it does not require any SP equipment on the OAN backbone, because service level procedures can be carried out remotely on a secure IP tunnel, just like a roaming GSM user is remotely authenticated by his home network. Particularly appealing is the "transparent roaming" property of this architecture, since the connection between the OAN and the SP is only logical and scales very well down to very small number of SP customers. Indeed, the commercial relationship between the OAN and the SP can be built "on-the-flight" through a clearinghouse when a user of a previously unknown SP visit, for instance, a HotSpot.

On the other hand, this approach requires more equipment, and, most of all, more management skills and effort on the OAN side. Moreover, the OAN must be autonomously connected to the Internet, which means that it must maintain connectivity through a lower tier operator. There are further topics, such as users traceability for legal purposes, etc. that have not been discussed here, and that might depend on local laws. Such topics affects for instance what informations, like IP addresses assignment, should be passed between OAN management and service operators.

We conclude this Section by pointing out three topics whose solution we deem of the utmost importance.

Standard AAA protocols in OANs. The integration of the standard AAA mechanism defined by 802.1x [17] provides for port-based authentication and would offer a powerful tool to enhance the global security of the system, given the possibility of introducing per-packet control. However, it is not clear whether the user-network interaction model foreseen in 802.1x is compatible with the OAN concept and to which of the previously described user-provider interaction model fits better.

Service Discovery and Selection. As the number of services offered and the number of service providers active on the open access network increases, methods to locate services and service parameters becomes important in order to improve the network usability. In order to allow users to become aware of the available services (whether on start-up or as a consequence of roaming), it is necessary to provide a service discovery mechanisms. Since the network can be ubiquitous and the available services can change seamlessly, these mechanisms needs to be automatic, which implies it must be possible for service providers to describe their services, and for those descriptions to be disseminated to the end-users requiring them. Using these methods, a user will be aware of present services, their characteristics (such as price), their requirements (such as terminal requirements) and necessary configuration parameters (if any).

Development of these methods require integrating results from research on authentication, authorization and accounting (AAA), research on service discovery and payment systems with the mechanisms for selection of service provider and has clear connections with pricing and location aware services discussed in Sections 6 and 5.4.

Roaming. Methods are called for to provide enhanced (nomadic) roaming between different attachment points, while preserving service provider relation and security level. In order to allow for seamless roaming among W-LANs owned and managed by different individuals or organizations, by users using a range of different applications and services, it is necessary to address two issues: (i) assess the requirements emerging from each service (or class of services), and (ii) develop a generic infrastructure that can support the seamless service mobility in each case.

5.2. Infrastructure and management support

Within basic network infrastructure and management there is a need for research in two areas: *differential forwarding*, and *network management mechanisms supporting growth.*

Mechanisms providing *differentiated forwarding* of traffic over the W-LAN are needed to separate operators and services. Specific techniques that could be used as starting points for this work range from implementing multiple L3 (e.g., IP) networks over the same L2 (e.g., Ethernet) network, to using VLANs, to virtual routed IP networks, and Multi-Protocol Label Switching (MPLS). Section 6 details an additional possibility based on pricing differentiation.

Under *network management mechanisms supporting growth* we consider the specific problems related to a wide deployment of active equipment at the network edge. These kinds of deployments call for a high degree of autoconfiguration in order to reduce the operational costs and thus make them economical feasible. For example, to facilitate large deployment of 802.11 APs, these should be equipped with mechanisms by which the base stations are configured without any manual intervention, furthermore supporting addition and removal with minimal system disruption. One trivial example is the channel choice based on minimal interference.

To support the extension of the OAN with new network segments providing for smooth growth, mechanisms for automatic configuration of network elements, such as layer 2 and layer 3 switches and routers, are needed. Such features are today available for end hosts through DHCP servers (an end host is automatically configured with IP address, subnet mask, default router etc.) and for IEEE 802.1 layer 2 switching systems (automatic address learning, build-up of forwarding information databases and loop detection mechanisms with the spanning tree algorithm). These kinds of mechanisms make it possible to establish and configure communication systems without in depth knowledge of the various technologies. However, these kind of auto-configuration tools are currently missing for layer 3 IP systems, which is considered as a main impediment for building out of IP-based metro access systems due to limited availability of personnel with adequate expertise and due the high cost of network outages due to mis-configuration. We argue that there is need for a solution that decouples the installation of a network element, which requires physical access, and the configuration, which requires networking experience but not necessarily physical access, in order to simplify router installation and configuration and thereby enable usage of IP routers close to the edge of the network.

5.3. Security

Secrecy, privacy and mutual authentication in commercial transactions are of the utmost importance in W-LANs, especially in public areas.

All "semantic-related" security issues, like for instance all credit card based transactions, where the user must be granted about the generalities of the counterpart, and a single leak in the security can have outcomes with legal implications, must be managed at the application level, that is the only level where the semantic of the information is known. This means that high security applications are not a business of the OAN.

On the other hand, a standard level of secrecy and privacy must be provided as a basic platform, and this is still a technical problem. WEP (Wireless Equivalent Privacy) can be used to build such a platform, but this still poses several problems. WEP was shown to be insecure and vulnerable to attacks (see [19] for instance); however, the algorithmic weakness of WEP is not the major concern. GSM security is as vulnerable if not even more insecure, but GSM is used without any concern, since it provides a basic level of security and privacy not easily broken without technical skills, and this is normally enough for a phone call.

The real challenges are on the protocol and management side. With presently available techniques, if WEP is to be used, APs and NICs must be manually configured so that everyone uses the same WEP key, and this is clearly unfeasible, at least in HotSpots. Besides, this manual configuration makes the WEP key static, which means that attacks on the system can be carried out with all the needed time. The real challenge is finding a suitable way to dynamically distribute keys in a secure way and to assign keys separately to each accessing user. Then WEP or any other equivalent algorithm can be safely used to provide the basic security and privacy platform.

The basic security platform must also provide a sort of mutual authentication mechanism by which users can be sure that the access point to which they are connected are among those deemed acceptable and trustable.

One final note on privacy: Some users may wish that their position remains unknown and untraceable apart from the service provider, which must know the user position to deliver the service. Since the OAN does not need to authenticate or bill users, the OAN does not need to know the users it is serving. Indeed, while receiving service, users are known to the OAN only through the MAC and IP address, both of which can be dynamically changed from one session to the next, ensuring that the user position and movements cannot be reconstructed by third parties. Some form of pseudonymous authentication mechanism can also be envisaged to shadow the identity of end-users when this is considered an issue, but some form if identification is needed. A simple example is assigning users a pseudonym that is built starting from the authenticating SP, like `<user-M><serv-pro-N>`

5.4. Location-aware services

A relevant piece of information in many context-aware applications for nomadic users is the users current location. Knowledge of the position, when combined with the user preferences, permits efficient service location, location-dependent alerting, and location-aware recommendation systems, the already mentioned provider selection being just the most basic one.

Support for location-aware services can add value to HotSpots and W-LANs in general. Provided that a local model relating signal strengths to location is made available by the OAN owner, individual user may determine their position with the accuracy of a few meters. A recommendation system that is based on a standard web browser and where models determining the relevance of a given URL in a given region are derived in an automated and adaptive way through the collaboration of users of the system is proposed in [4]. Other proposals can be found in the literature cited there. Open issues include the following.

- Protect privacy of the mobile user (the user knows his location but the system does not).
- Avoid overloading the user with undesired information (spam), by filtering the information according to user-defined rules and by accurately identifying the information source (e.g., a user may decide to accept information coming only from trusted parties with high reputation).
- Define and adopt standards to describe location.
- Provide scalability so that local information collected from the different OANs is managed in a distributed way to support nomadic users.

6. Assuring QOS through pricing

An OAN should aim at maximizing the social welfare of the users, by providing quality of service appropriate to the criticality of the different applications, and it should be assured sufficient resources to cover all costs and possibly future expansions and upgrades. Two well know general economic approaches, see for example [6], are the intervention of an illuminated social planner to fix prices and regulate usage priorities or the intervention of the invisible hand of the market, acting while participants make decisions in a distributed and uncoordinated way while aiming at maximizing individual utilities.

The heterogeneous nature of different OANs makes detailed regulation a daunting task. As an example, determining the priorities of different connections to allocate bandwidth or to decide about admitting a new connection request cannot rely on the assumption that all users cooperate by providing true declarations, while detailed checks of the declarations are not feasible. Dynamic pricing mechanisms can be used to encourage an efficient use of the resources and to signal the need for network expansion. Let us point out that pricing is not necessarily related to cash exchanges.

Focusing on HotSpots, the specific driving forces characterizing the Wi-Fi evolution are: the low cost-barrier to realize an access point, the emerging tendency to deregulate ISM spectrum for communications to create a secondary wireless market [7], and the need to avoid excessive interference by placing too many access points of different networks in the same area (OANs go in this direction by encouraging infrastructure sharing by different service providers).

A price-based policy for the access control in a Wi-Fi hot spot has been presented in [5]. The policy, named Price-based Congestion Control (PCC), controls the hot spot traffic by dynamically determining the access price as a function of the current load in the hot spot. The general layout of the proposed pricing mechanism consist of the following:

- For each successful transmission the sending mobile user is charged *packet price.* We use per-packet charging and not per-byte pricing for several reasons. It favors use of long packets, which gives higher utilization in 802.11 networks; queues are maintained in packets and not bytes; variable transsmission speeds due to channel fluctuation make the amount of information contained in packets change in time, per-byte pricing increses the risk of messing up between congestion and channel quality fluctuations.
- The price is periodically announced by the access point, so at any moment all associated mobile terminals are aware of current price value. Price announcements can, for example, follow beacon frames, which are typically transmitted every 102400 μs $\approx$ 0.1s.

This scheme implies fast-timescale dynamic pricing, with price updates each second or even faster. The speed is too fast for human users to respond, so a user-agent software is expected to run on a mobile station and absorb the pricing

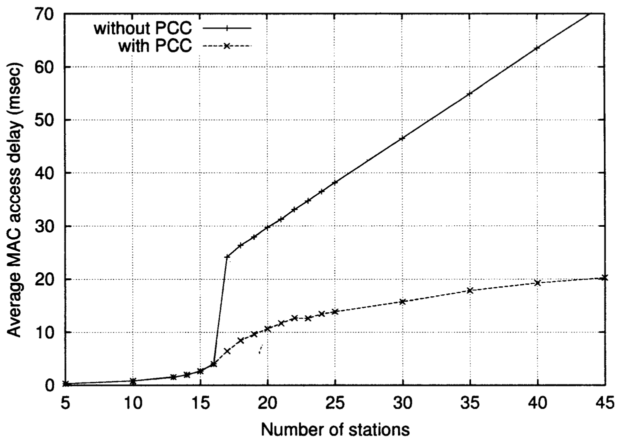

Figure 6. Average MAC access delay for mobile station in Hot Spot with different total number of mobiles, with and without dynamic pricing.

complexity. Pricing in this case is not necessarily related to money, but can, for instance, refer to access grants in moments of low congestion.

Packet delay is one of the major QoS parameters, which is crucial for real-time multimedia applications. Acceptable level of round-trip delay is typically presumed to be about 100 ms. Therefore, access delay in MAC layer must be much smaller in order to provide sufficient QoS. Implementing dynamic pricing can significantly decrease MAC access delay in case of high load.

Figure 6 reports an example of PCC application obtained through simulations. The PCC scheme and general setup are those described in [5]. We simulate a single access point with an increasing number of mobile users generating traffic. The traffic is a high-level model of elastic traffic, where the packet generation rate can be slowed down through any suitable back-pressure mechanism, whose aim is reducing the rate with with packets are offered to the MAC protocol. Such a mechanism may work under the IP level.

The left part of the plot corresponds to a light load which is less than channel capacity and therefore the pricing mechanism is not active. As the load increases with the number of users, at some point congestion starts, and dramatically increases the access delay due to the backoff mechanism of the CSMA/CA protocol. Dynamic pricing smooths the transition, reduces the delay and slows down its growth. In this case, the QoS improves because users with elastic demand defer some transmissions if network is approaching congestion (signaled by price increase).

This pricing mechanism is designed to be used in wireless HotSpots and features very low overhead and no requirements for executing complex algorithms on mobile terminals. Other schemes that can be used in wireless networks as well, for example those developed in [12] and, [2].

There are still a number of open issues that require investigation:

- How to reduce complexity for the final user who typically does not like dynamic pricing mechanisms. Appropriate software agents can be installed on the mobile terminal so that they monitor network status as signaled by advertised prices and aim at maximizing user utility depending on preferences and budget limits declared at initialization.
- Dynamic pricing algorithms must be robust to various types of user behavior. Malicious users can attempt to influence price if there is a possibility for him to benefit from it, for instance jamming the network (price rises), so that other users disconnect (price drops) and the disturber sends his traffic.
- Commercial HotSpot providers themselves could be induced to generate congestion only to increase revenues, e.g., by encouraging wasteful usage by some price-elastic users so that price-inelastic users are charged more. We do not think this scenario will ever happen, because the result of such an action will rather be a bad service for a high price, which will probably not increase revenues in a competitive environment. However, if OANs are managed by non-profit organizations, this scenario is even less probably, since they are a possible way to generate trust and avoid improper pricing mechanisms (i.e., price discrimination or personalized pricing).
- Network externalities and possible public intervention. It is well known that a network value for a customer grows as more users are connected. E.g., the more people are reached with a Wi-Fi terminal, the higher the motivation for participating and financing a wireless OAN.
- Roaming in a trusted environment. QoS and pricing becomes challenging in a roaming environment characterized by many actors (e.g., many OANs belonging to different organizations). Clearinghouses could be appropriate third parties to guarantee all participants and they can ask the different OAN organization to ensure roaming agreements conforming to certain standards and enforce compliance by periodic auditing.

7. Conclusions

Open access networks are a new concept in the telecommunication market that seemingly brings benefits to all involved actors. We have discussed their business model, and why we deem they might offer a competitive edge to communities and countries that adopt this new model of communication infrastructure. We have also discussed reasons for departing from the traditional model of vertical integration of the services, from the hardware infrastructure to value added services, that is mostly adopted by operators and that stems from the old monopolistic management of telephony systems.

In spite of the fact that OANs bring benefits to all, they will not happen by themselves and many technical, cultural and economical details have to be solved. Details in the bootstrapping process still remain to be discovered and will foster research in the next future. We have discussed some of the technical challenges related to OANs, but the most formidable are on the cultural, legislative and economical side.

Finally, we have delved deeper into the subject of wireless OAN evolution, presenting some preliminary simulation results based on pricing models. They represent business models that show the viability and proof-of-concept of access sharing in OANs and HotSpots.

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