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Routed Mesh Networks:
Wireless Broadband for Consumers

Ari Leppä

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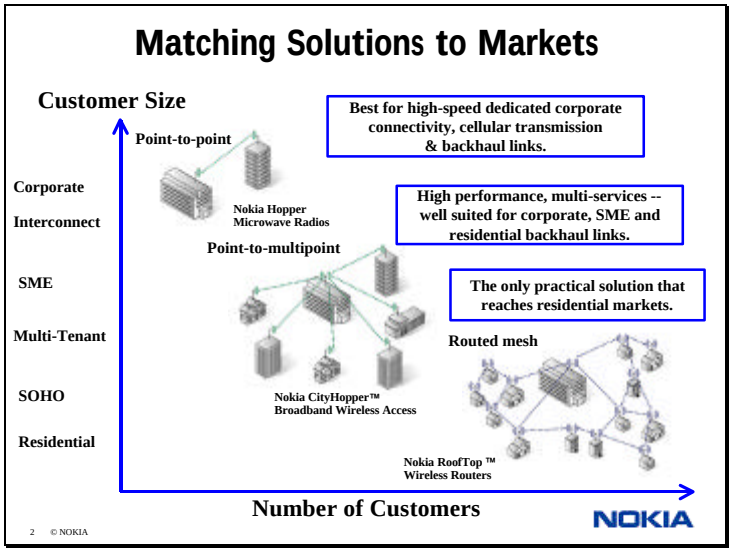
Matching Solutions to Markets
Customer Size
Point-to-point
Best for high-speed dedicated corporate connectivity, cellular transmission & backhaul links.
Nokia Hopper Microwave Radios
Corporate
Interconnect
High performance, multi-services -- well suited for corporate, SME and residential backhaul links.
Point-to-multipoint
SME
The only practical solution that reaches residential markets.
Multi-Tenant
Routed mesh
SOHO
Nokia CityHopper™ Broadband Wireless Access
Residential
Nokia RoofTop ™ Wireless Routers
Number of Customers
2 © NOKIA
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Requirements for Success

Coverage

- No line–of-sight requirement to a single point
  - Base station site acquisition and cost
  - Redundancy
- Adaptive to different topographies

Low cost, incremental deployment

- Minimal upfront infrastructure costs
  - Build as you go
- Low-cost installs - no RF expertise
  - NO antenna pointing

No Line-Of-Sight Requirement to a Single Point

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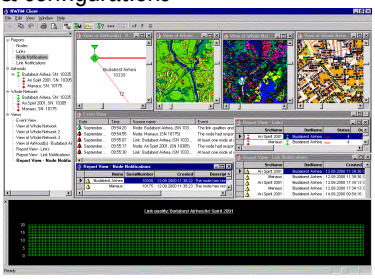
Requirements for Success

Simple, Reliable Operations

- Easily increase capacity per square mile
- Remote upgrades, changes & configurations
- No antenna re-pointing
- No interruption of service
- Network management
  - Technical support
  - Sales support



No Recurring Truck Rolls

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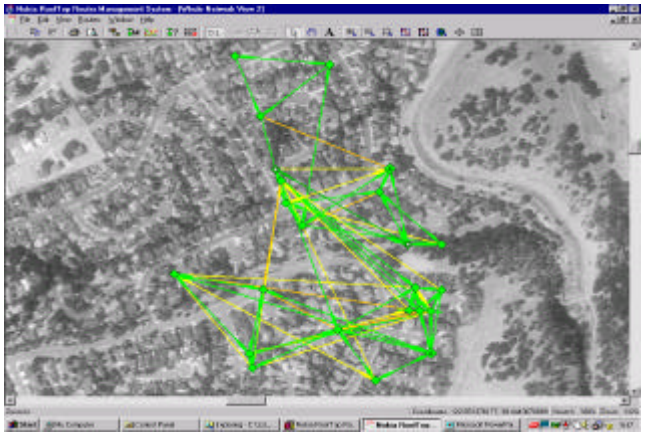
Routed Mesh Network



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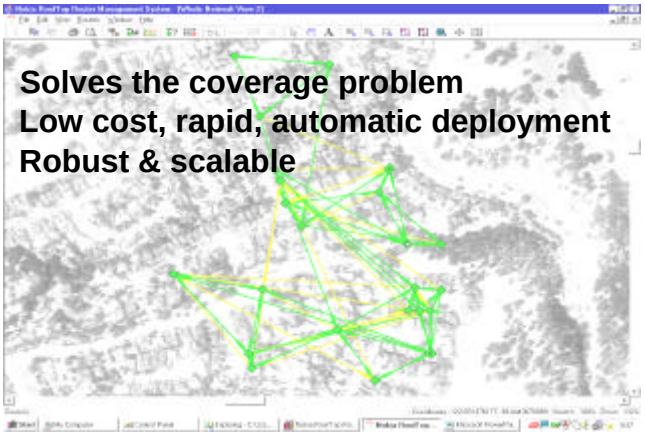
Routed Mesh Network



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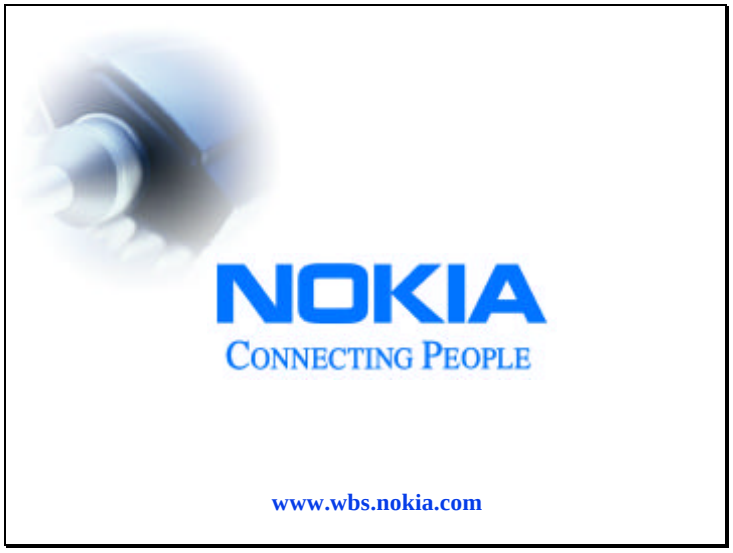
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Nokia RoofTop™ Wireless Routing
Technology White Paper

Introduction

The rapid growth of the Internet in the past five years has created a two-fold situation. One, the Internet has become one of the single most important tools for people and businesses to communicate with each other. Two, the importance of the Internet has necessitated that people have quick and ready access to it from any location. These two factors have led to an increased dependence on the Internet that is driving up access bandwidth demands at a pace faster than the wired infrastructure can keep up with. Upgrading wired infrastructure to provide high-speed and remote Internet access is costly, complicated and time consuming. The result is a bottleneck at the Internet access point—the last mile of Internet infrastructure. Today's wireless broadband networks make high performance Internet access possible where wired broadband infrastructure is impractical. Wireless broadband networks avoid the upfront costs and delays of building or upgrading a wired infrastructure. However, for wireless broadband networks to be practical for residential and small business markets, the infrastructure must be low-cost, robust to changing environments, easy to deploy and scalable with market demand. Today's high-performance wireless networks are too expensive to deploy to small business and residential markets.

What has kept wireless broadband technology from being practical for these price-sensitive, mass markets is a combination of technological constraints and deployment costs. High-performance wireless connections require a clear line-of-sight between links. In many neighborhoods and local business communities, buildings, trees, hills and the curvature of the earth make line-of-sight difficult.

Technology advancements are making the promise of high-speed wireless data a reality for mass consumer markets. License-free spectrum bands eliminate the need for an operating license and the high fees of bidding for spectrum. This opens up market opportunities to a wide range of carriers and service providers. In addition, new wireless specific protocols enable routed wireless mesh networks that simplify line-of-sight requirements, and optimize the efficiency of the spectrum. And advancements in wireless link intelligence enable self-configuring and self-healing networks that are simple to deploy and adaptable to changing situations.

These new technologies enable a new type of network. A network that anyone can deploy without a large, upfront investment in RF engineering or infrastructure. A network that is less expensive to deploy to residential markets than either a new wired infrastructure or a wireless network based on a client/base station architecture. These new networks emulate the topology and protocols of the Internet itself, but are optimized for wireless high-speed data transmission. Nokia is a pioneer in

this new technology with a wireless broadband solution called the Nokia RoofTop™ Wireless Routing network.

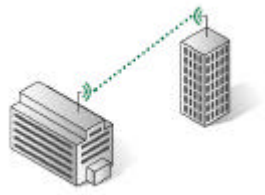
The key components of the new Nokia RoofTop solution are:

- **Routed mesh network architecture**-a distributed, routed, mesh network architecture that simplifies line-of-sight problems and scales much more cost effectively than a client/base station, point-to-multipoint architecture;
- **Wireless routers-** a combination of a high-performance RF modem with specialized wireless networking software that optimizes the network performance while ensuring full IP support and robust and seamless IP routing;
- **Wireless operating system**- a suite of specialized protocols and wireless intelligence that optimize the use and efficiency of the spectrum and ensure an adaptive and robust network;
- **Deployment and management**- self-configuring routers and a graphical user interface (GUI)-based element management tool make installation and ongoing management quick and easy.

Wireless Network Architectures

There are three types of wireless network architectures: point-to-point, point-to-multipoint and multipoint-to-multipoint mesh. Each type of network is best suited for different types of applications. Combining various types of systems creates solutions that can scale to reach large market segments.

Point-to-Point Networks



A point-to-point network is the simplest form of wireless network, composed of two radios in direct communication with each other. Point-to-point links are well suited for high performance, dedicated corporate connections or high speed interconnect links. These links are quick to deploy individually, but do not scale to create large networks effectively.

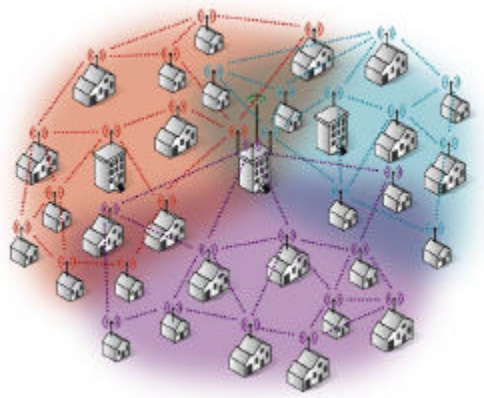
Point-to-Multipoint Networks

A point-to-multipoint network is a shared link between a base station radio and client radios at multiple sites. This type of network is easier to deploy than a network using point-to-point radios because adding a subscriber only requires new equipment at the subscriber site, not at the basestation site. However each remote site must be within range and line-of-sight of the base station, thus limiting coverage to a single

hop.

Point-to-multipoint networks share the channel bandwidth between several subscribers. By statistically multiplexing packet-switched traffic, the networks can be provisioned to handle peak burst rates for each subscriber without having to dedicate the bandwidth to them when not needed. There are multiple types of point-to-multipoint networks, including high-bandwidth solutions operating in licensed spectrum (such as local multipoint distribution service [LMDS]), and lower speed 802.11 point-to-multipoint solutions. Point-to-multipoint networks work well in downtown urban environments, but do not scale well to reach dense pockets of homes or small businesses due to line of sight restrictions.

Multipoint-to-Multipoint Mesh Networks



Routed, mesh networks mirror the structure of the wired Internet. They are the most flexible and cost-effective solution for extending broadband services to a mass market. Each radio in the network becomes part of the infrastructure and can route data through the wireless mesh network to its destination, just like the wired Internet. A routed mesh network simplifies line-of-sight problems and scales more cost effectively than a client/base station architecture because each node only needs line-of-sight to one other node in the network, not all the way to the ultimate destination of the traffic. This extends the reach and coverage of the network with a minimal amount of network infrastructure and interconnection costs. Traffic can be routed around obstructions rather than needing to deploy additional base stations for line of sight in densely populated diverse geographical locations. And the more routers that are added to the network, the more robust and far-reaching the network can become. This simplified line-of-sight and lower overall infrastructure costs makes routed mesh networks the fastest and least expensive way to reach dense pockets of homes and small businesses.

As a pioneer of this mesh design, the Nokia RoofTop network utilizes a new type of wireless router and omni-directional antennas so each node in the network can communicate with nodes in any direction. The omni-directional antennas offer a 360-degree range and do not require precise pointing or steering. Consequently, additional wireless routers can be added in an ad hoc and incremental fashion, to grow with the number of new subscribers.

Wireless Routers

In order to create an efficient and robust wireless, routed mesh network, wireless routers need three components:

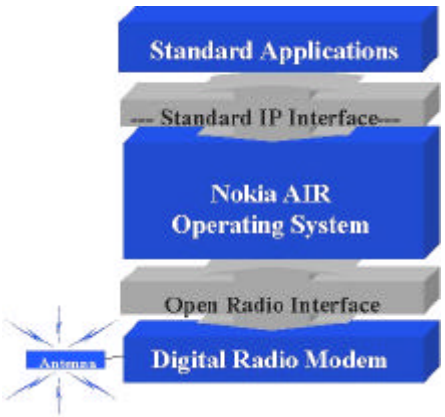
- full TCP/IP protocol suite support;
- wireless operating system that optimizes the wireless network performance and robustness;

- a high-performance digital RF modem.

Radio technology is advancing rapidly. As a means of de-coupling the innovation timelines of the RF industry and the data networking industry, Nokia is leading the development of open radio interfaces and standards that enable the growth of a large, horizontal broadband wireless market. This architecture enables the wireless operating system to be used in different types of wireless routing products that take advantage of innovations in digital RF technology as they become cost effective for different markets. It enables Nokia to select best-of-breed RF modems for different applications, creating a suite of wireless router products.

Wireless-aware Protocols

Routed wireless mesh networks need specialized protocols that operate efficiently in the communication environment that is unique to multihop wireless networks. Combining an IP protocol stack with the standard underlying protocols that are designed for wired networks with an RF modem will result in a wireless network with marginal performance, at best. Wired protocols assume that every node can hear every other node and connectivity is clear—it is either there or it isn't. There are no marginal or transitory links. Outdoor, multihop, wireless networks are different. From the media access control (MAC) layer through the routing layer, new protocols must be used that are specifically designed to deal with their unique attributes, efficiently.



Nokia has developed the Nokia AIR Operating System—a wireless Internet operating system that consists of a suite of IP and wireless networking protocols. This protocol suite extends the traditional TCP/IP stack to provide efficient and robust IP-based networking in multihop, wireless mesh networks. It abstracts the physical RF modem from the operating system, enabling independent networking software that can work with a wide range of RF modems.

The Nokia AIR Operating System consists of four primary parts:

- **Channel access protocols** efficiently schedule transmissions to avoid collisions and efficiently reuse spectrum;
- **Reliable link and neighbor management protocols** ensure reliable transmissions on a hop-by-hop basis, and manage the automatic adaptation to changes in the network topology by monitoring the status of neighbor links;
- **Wireless multihop routing and multicast protocols** maintain performance- optimized routing tables, and enable an efficient multicast capability;

- **Standard Internet protocols** provide the standard set of protocols and tools (TCP, IP, UDP, SNMP, RIP, ICMP, TFTP, ARP, IGMP, Proxy-ARP, DHCP Relay, DHCP Server, NAT) for seamless integration with the wired Internet.

Ancillary protocols manage key issues such as network security, dynamically controlling the RF waveform to prevent eavesdropping and ensuring the authenticity of new network nodes before they are allowed entry into the network. Other utility protocols support such tasks as remote network management and over-the-air distribution of software updates. In sum, the Nokia AIR Operating System enables a wireless network that is efficient, adaptive, secure and scalable.

Channel Access Protocols

The wireless router's RF channel is characterized as a local broadcast medium. Unlike traditional broadcast mediums such as wired Ethernet networks, in which a transmission by any computer can be heard by all other computers on the network, transmissions in a multihop wireless network are heard only by neighboring routers. Therefore Ethernet algorithms, such as Carrier Sense Multiple Access (CSMA), are ineffective at scheduling channel access for the nodes in the wireless network.

In multipoint wireless environments, the hidden terminal creates a problem in which two wireless routers A and C, who may be out of range to communicate directly, must coordinate their transmissions to wireless router B who can hear both, to avoid packet collisions at B. A similar problem occurs even if C's transmission is intended for another wireless router (D). This issue becomes quite complex in large and dense networks.

The responsibility of the channel access protocols is to schedule transmission to avoid collisions while maximizing the overall utilization of the RF spectrum. This is accomplished by a set of algorithms that perform three functions:

- independently schedule network management packets on a common channel to avoid collisions within each two-hop extended neighborhood;
- cooperatively schedule non-interfering data burst transmissions between pairs of nodes, using multiple RF channels simultaneously to maximize overall network throughput; and
- employ frequency agility, coding, and power control to avoid interference beyond the extended neighborhood.

Reliable Link and Neighbor Management Protocols

The bandwidth of the air link is a scarce resource, and more prone to bit errors than the wired medium.

The role of the reliable link and neighbor management protocols is to perform network synchronization and to manage the links to each neighbor Internet radio. They also control the transmission parameters to account for varying channel conditions due to external interference, channel fading and inclement weather. Specifically, reliable link protocols provide the following capabilities:

- enable network synchronization through a fully distributed synchronization algorithm that eliminates the need for a master network clock;
- perform efficient hop-by-hop reliable packet delivery; and
- Monitor and manage link conditions, such as power, maximum packet size and error-control coding rates, between neighboring radios.

Multihop Routing and Multicast Protocols

Once software protocols successfully schedule and transmit packets between neighbors, the challenge is to provide the network-wide coordination needed to ensure that packets are efficiently and reliably forwarded over multiple-hop paths to their intended destination. Unlike traditional routing protocols for wired networks, these routing decisions impact overall network efficiency. The Nokia AIR Operating System routing and multicast protocols perform the following functions:

- ensure robust routing in a dynamic, ad-hoc network through automatic detection of new or missing links, without manual administration;
- automatically select the highest quality, least congested paths, maximizing overall network throughput; and
- provide an efficient multicast mechanism across the wireless broadcast channel, transmitting once per node rather than once for each neighbor link.

Spread Spectrum RF Modems and Network Authentication

For many users, the security of the communications system and of the information it transports is critical, particularly when wireless links are involved. It is generally necessary to ensure that the communications system is secure from the following threats:

- disclosure of user data traffic to eavesdroppers;
- unauthorized network participation as an active node; and
- unauthorized access to nodes attached to the wireless network.

The responsibility of the RF modem and security protocols is to protect the network and the traffic it carries from these threats.

The spread spectrum radios used in the Nokia RoofTop Wireless Router were originally developed by the military to prevent eavesdrop breaches. Frequency-hopping spread spectrum radios have to know the exact timing and hopping pattern in order to eavesdrop on a network. Direct sequence spread spectrum radios have to know the exact data rate, center frequency and spreading code of the other radio in order to eavesdrop. The Nokia AIR Operating System allows network administrators to control the hopping pattern or spreading code of the wireless routers. Thus, security can be easily controlled.

This operating system also provides security through node authentication. The Nokia AIR Operating System uses network codes and 16-bit authentication keys to validate nodes as they try to join a

network. When a node tries to join a network, it must present a valid network authentication code before being recognized as an authorized node and allowed to join the network.

An intrusion protection packet-filtering feature also provides basic firewall-like capabilities to prevent hackers from accessing the network.

Nokia's wireless routers follow the security model of the Internet. If data encryption is needed, the end application can send encrypted information across the wireless and the wired links transparently. The routers are unaware of whether the data is encrypted or not as it is forwarded. Therefore, encryption can be used reliably.

Deploying and Operating a Wireless Broadband Network

To make wireless broadband networks practical for residential deployment, the network must be simple and low-cost to deploy and maintain. Thus:

- no special RF skills should be required to install subscriber nodes;
- the wireless network should be able to be deployed rapidly and cost effectively, without extensive upfront infrastructure;
- the wireless network should be adaptive to continual network and environmental changes.

Letting demand and actual traffic flow drive the wireless local loop deployment is much more cost-effective than trying to anticipate coverage and bandwidth needs ahead of time. Multihop networks make this easier than point-to-multipoint networks because there is not as much RF planning required. However, for ad-hoc node deployment to be practical, the network must adapt to changes in link quality and the overall network topology automatically rather than requiring manual reconfiguration with every change.

This same adaptive intelligence creates a network that is robust to environmental changes as well. Over time, new buildings, temporary obstructions or growing trees, may block what were robust links. Adaptive, routed mesh networks make this less problematic since traffic can be automatically re-routed through an alternative path if a link becomes unavailable. In dynamically changing networks, robust network operation requires nodes to have the ability to adapt to changes in link availability and quality in real-time without requiring intervention by a network administrator.

The Nokia AIR Operating System continuously monitors the status and quality of links, and makes real-time routing decisions based on the current network status. New nodes are authenticated and assimilated into the network topology without manual reconfiguration. Networks also automatically reconfigure and adapt when nodes are removed from the network.

Nokia RoofTop Router Management System

For a fixed wireless broadband network to be practical to deploy and operate, it not only requires the adaptive link and routing intelligence of a robust operating system, but also an easy to use configuration and management tool. This tool would enable network administrators without extensive RF engineering experience to manage day-to-day network administration tasks remotely.

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Nokia has developed the Nokia RoofTop Router Management System (RMS) for exactly such a purpose.

This RMS enables administrators to configure, monitor and upgrade their Nokia RoofTop networks over-the-air, using a dynamic graphical user interface (GUI). Both simple tasks, such as assigning IP addresses, and more advanced network administration, such as authenticating network membership, or managing network capacity are quick and easy using the RMS.

Conclusion

The Internet has rapidly become the most important medium for people and businesses to communicate with each other, and accessing it quickly from any location has become a critical need. Our dependence on the Internet for communication and business is driving up access bandwidth demands at a pace faster than the wired infrastructure of traditional providers can meet. The resulting bottleneck at the Internet access point—the last mile of the Internet infrastructure—demands an alternative solution to wired Internet carriers.

The solution: a fixed wireless broadband Internet. Wireless broadband networks make high performance access networks possible where wired infrastructure is impractical. They can be deployed more quickly and cost effectively than wired broadband networks. The right kind of wireless solution can be deployed incrementally and driven by demand, rather than requiring extensive RF planning and expensive upfront infrastructure deployments.

The Nokia RoofTop network solution integrates the most advanced technological innovations of fixed wireless broadband networks. The routed mesh network design enables each node to function as an intermediary router, which simplifies line-of-sight problems and scales much more cost effectively than a client/base station architecture. The Nokia AIR Operating System provides a suite of protocols that efficiently controls channel access, link and neighbor management, routing and multicasting in a multihop wireless environment. This operating system also ensures a reliable, robust network that can adapt to changes in real-time. The Nokia RoofTop Router Management System enables administrators to easily configure, monitor and upgrade their Nokia RoofTop networks using a dynamic graphical user interface. Finally, spread spectrum RF modems provide a secure yet affordable solution to reach competitive consumer markets.

Together, all of these innovations add up to a solution that redefines the way broadband Internet access is delivered. The Nokia RoofTop solution eliminates the cost and delay of traditional wired approaches and enables more robust and far-reaching coverage than other wireless broadband networks. This network provides a new way to deliver broadband access to neighborhoods and small office markets that is more flexible, cost-effective solution than alternative wireless approaches.