Integrating Short-Range Radio Technologies Into Next-Generation Wireless Networks

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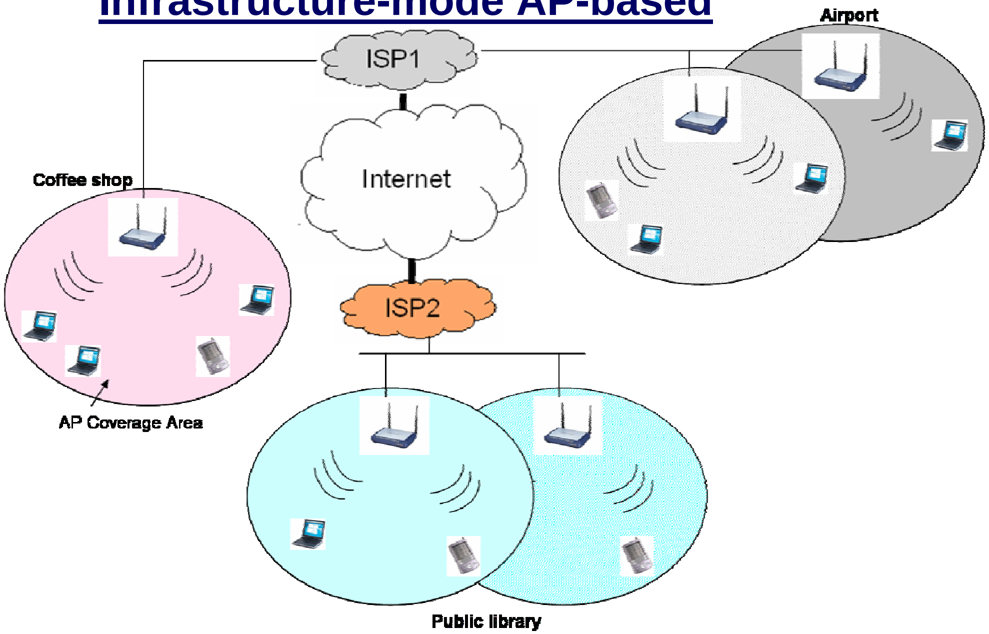
Metropolitan-area wireless access based on 802.11: WLAN Hot Spots

Examples: Taiwan's CyberCity Project, various commercial deployments

Infrastructure-mode AP-based



These systems focus on providing broadband portable/mobile access in high-density urban "hot-spots"

- Architecture limited by the need for large numbers of access points
- Relatively high capital costs and wired backhaul link costs
- Single radio access hop tends to assure good performance

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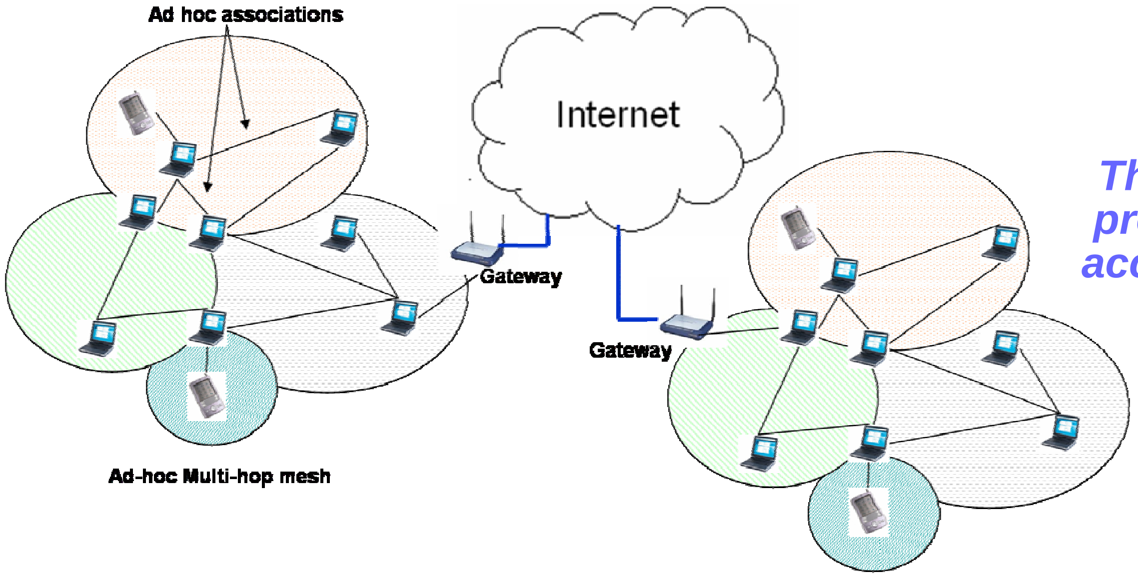
Metropolitan-area wireless access based on 802.11: Mesh Community Networks

Examples: LocustWorld, CuWiN (Champaign-Urbana Community Wireless Network)

Ad-hoc mesh based



These systems focus on providing medium speed access in medium density urban and suburban scenarios

- Reduces the need for wired APs via ad-hoc wireless mesh infrastructure
- Multi-hop links – reduced throughput per node, variable delays
- Potentially lower capital and operating costs relative to WLAN hot-spots

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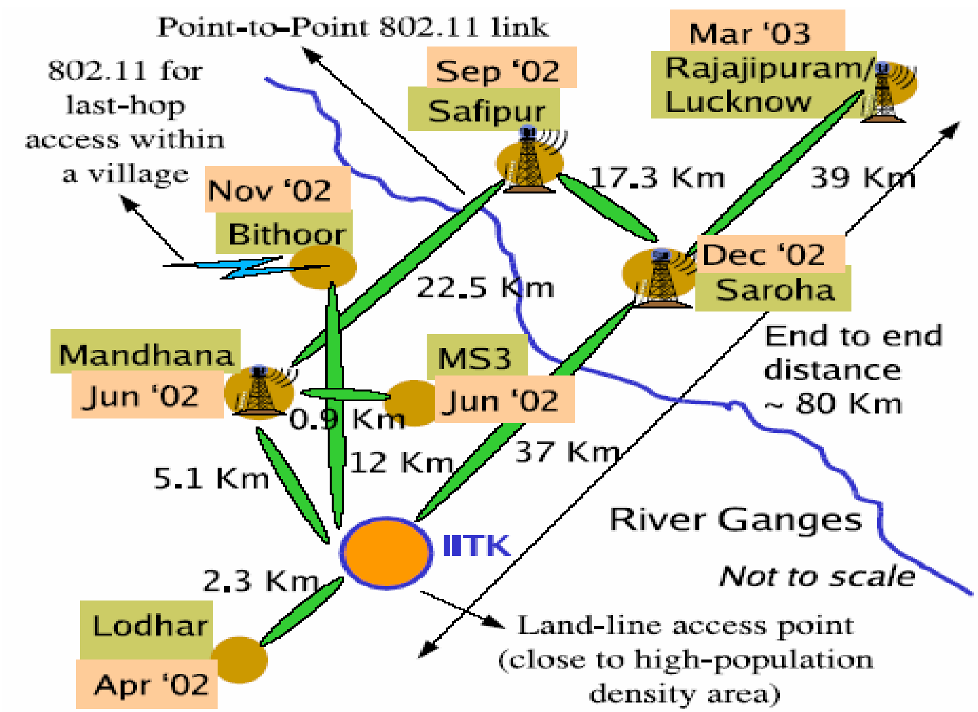
Rural & metro wireless access based on 802.11: Digital Gangetic Plains Project



From "*Turning 802.11 Inside Out*", Praveen Bhagwat, et al, *HotNets - II*, Cambridge, MA, USA, Nov 2003

First large-scale attempt to use 802.11 for outdoor rural networks

Technology focus on extended range 802.11 for wide-area mesh

Related Work:

TDMA-based MAC for Rural Mesh Network[1]

[1] "Revisiting MAC Design for an 802.11-based Mesh Network", Bhaskaran Raman and Kameswari Chebrolu, Third Workshop on Hot Topics in Networks (HotNets-III), 15-16 Nov 2004, San Diego, CA, USA

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Objective of this talk

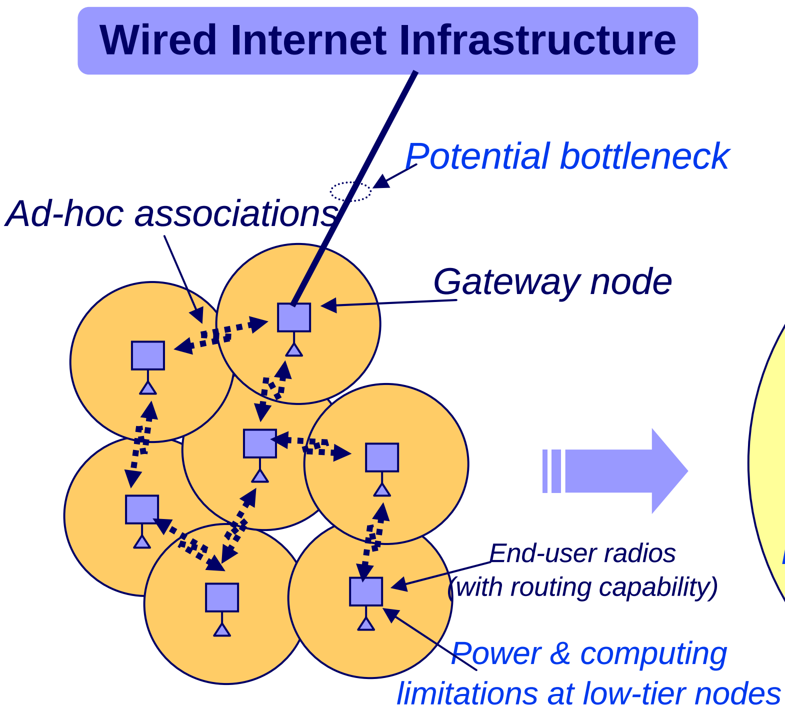
Further investigation of the feasibility of mesh network technologies for metro area applications:

- WINLAB's Self-Organizing Hierarchical Network (SOHAN) with improved capacity/performance
- System capacity & cost evaluation for example medium density metro area
- Prototype validation of mesh network protocols and emulated system performance using ORBIT testbed

Mesh Architecture: Flat vs. Hierarchical

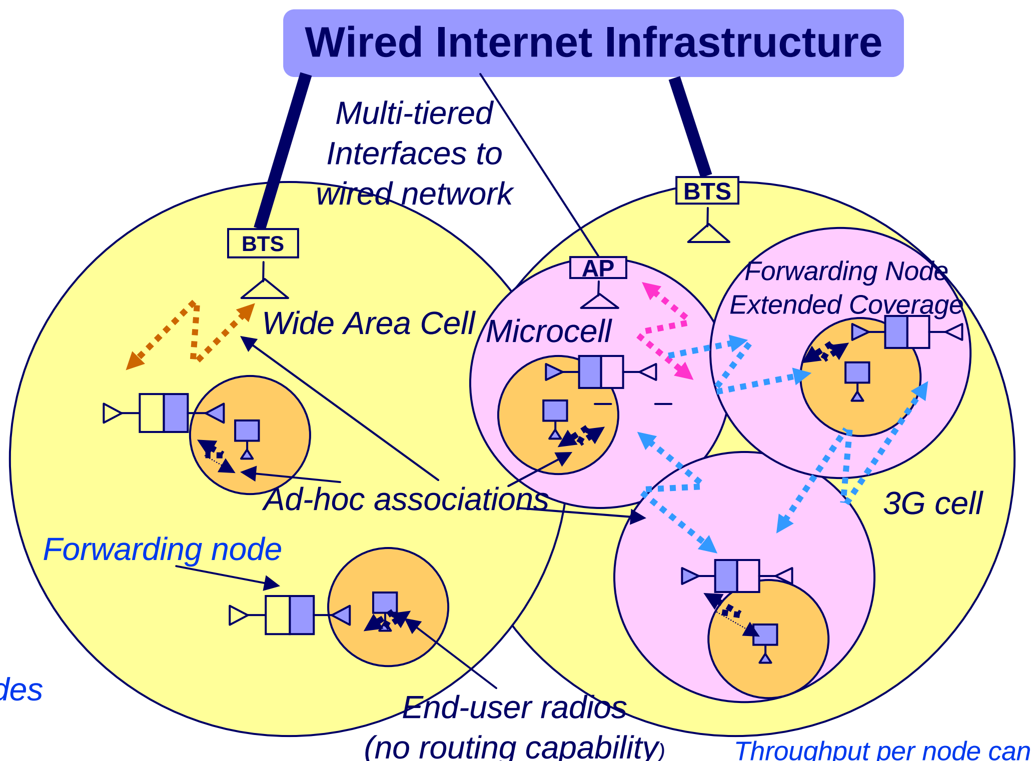
Hierarchical structure is essential, and helps to achieve

- Scalability, i.e. improved max throughput and delay/QoS
- Effective integration with 3G/4G, WLAN and Internet
- Improved coverage & power consumption at subscriber radios



“Flat” mesh network with ad-hoc routing

Throughput per node scales ~ 1/sqrt(n)



Throughput per node can scale with right ratio of FN’s, AP’s

Hierarchical architecture

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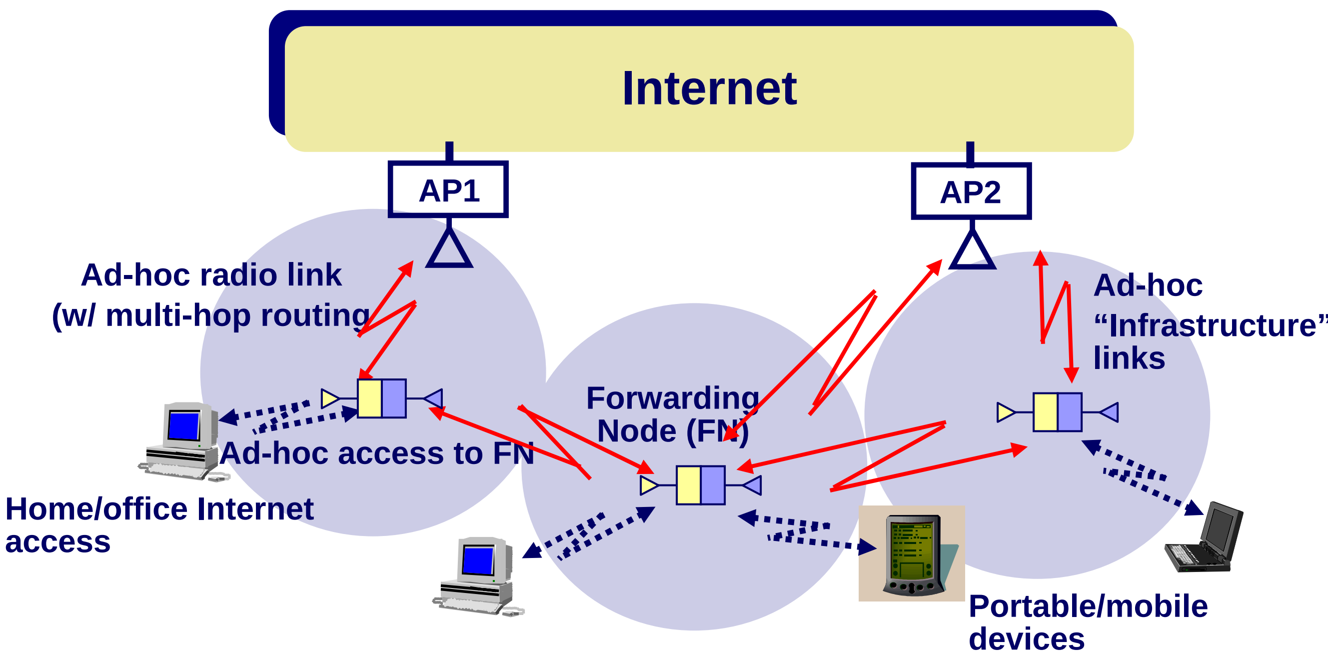
SOHAN Architecture: Components

Tier 1: Low-tier subscriber nodes (MN)

Tier 2: Forwarding nodes (FN) with multiple radio interfaces (can operate on different frequencies)

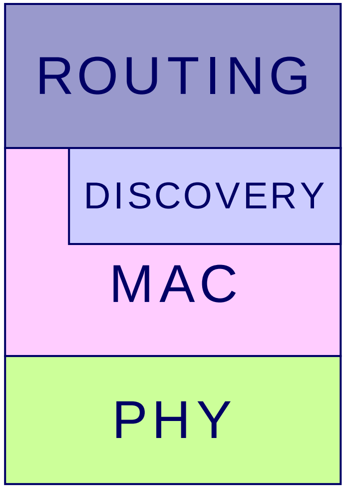
Tier 3: Wired Access Points (AP)



Self-organizing hierarchical ad-hoc mesh network

SOHAN Architecture: Protocols

- Bootstrapping Mechanism
  - **Configuration in terms of channel assignments and initial transmit power level settings**
- Discovery Mechanism
  - **Filters links made available to the routing protocol based on desired objective function – reduces routing overhead**
  - **Supports heterogeneity – Each node can apply a different objective in choosing its neighbors depending on its capabilities**
  - **Supports multi-channel operation of network**
- Routing Mechanism
  - **Uses the “logical” topology information presented by the discovery mechanism to create and maintain local “neighbor tables”**
  - **Only FNs and APs participate in routing**

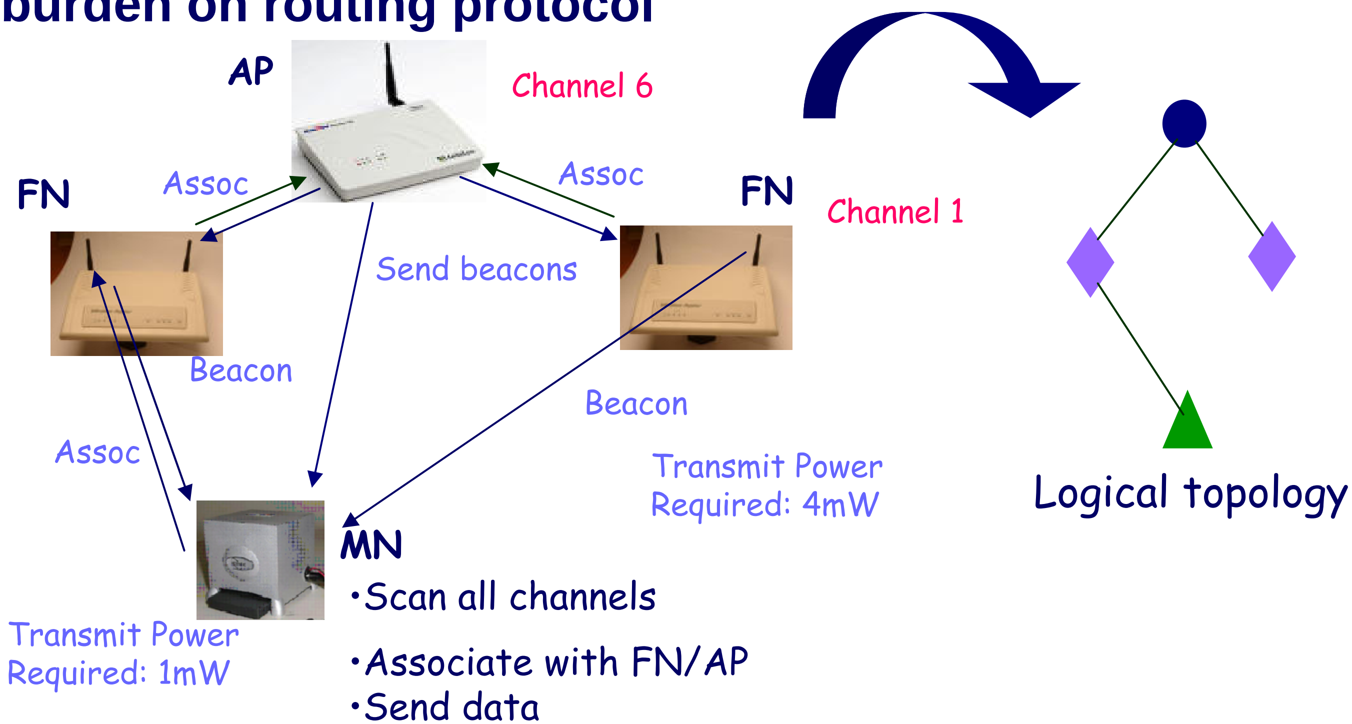


Ad hoc Discovery: Protocol Concept

Creates efficient ad-hoc network topology just above MAC layer in order to reduce burden on routing protocol

Interface One
- Send beacons
- Accept Associations
- Forward MN Data

Interface Two
- Scan all channels
- Find minimum delay links to AP
- Associate with AP



Beacon Frame Format

Source MAC	Broadcast MAC	Node ID	Node Type	Channel	Packet Type	Sequence Number	Transmit Power	RSSI

Generated by application layer (Source MAC … Sequence Number)

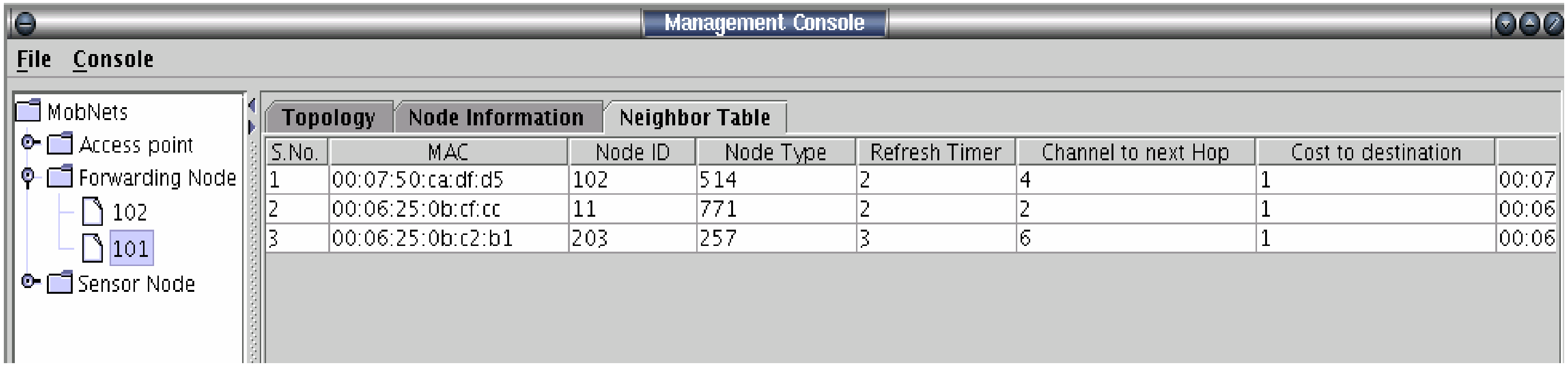
Appended by driver (Transmit Power, RSSI)

Integrated Discovery and Routing

Routing Mechanism integrated with discovery protocol

- DSDV-like distance vector based
- Uses information collected during periodic discovery phase in order to find neighbors
- Maintains local neighbor tables at each node
- Neighbor tables exchanged periodically between FN's and AP's
- MNs do not participate in routing – hence energy savings

Neighbor table at an FN



S.No.	MAC	Node ID	Node Type	Refresh Timer	Channel to next Hop	Cost to destination	
1	00:07:50:ca:df:d5	102	514	2	4	1	00:07
2	00:06:25:0b:cf:cc	11	771	2	2	1	00:06
3	00:06:25:0b:c2:b1	203	257	3	6	1	00:06

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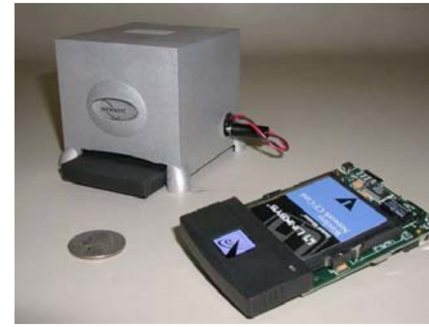
SOHAN Prototype

HARDWARE



PLATFORM

Access Point

US Robotics 2450 AP

AMD Elan SC400 processor

1 MB Flash, 4 MB RAM

Prism-2 based PCMCIA card

Forwarding node

Compulab 586 CORE

AMD Elan SC520 CPU

2 MB NOR flash + 64 MB NAND Flash on board

Dual PCMCIA slots

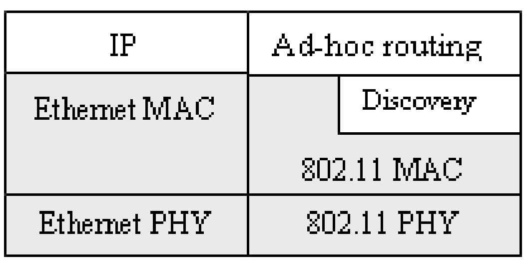
Mobile Nodes

Intrinsyc Cerfcube

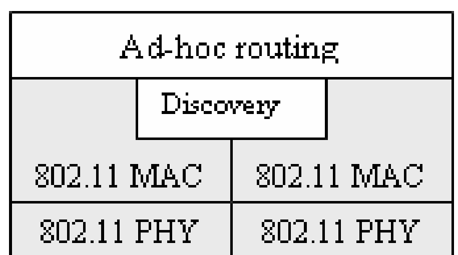
Intel PXA 250 (XScale processor)

CF-based wireless support

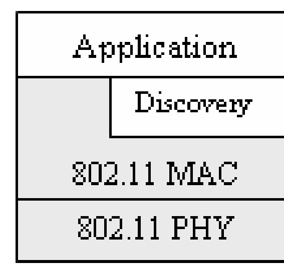
PROTOCOL



AP

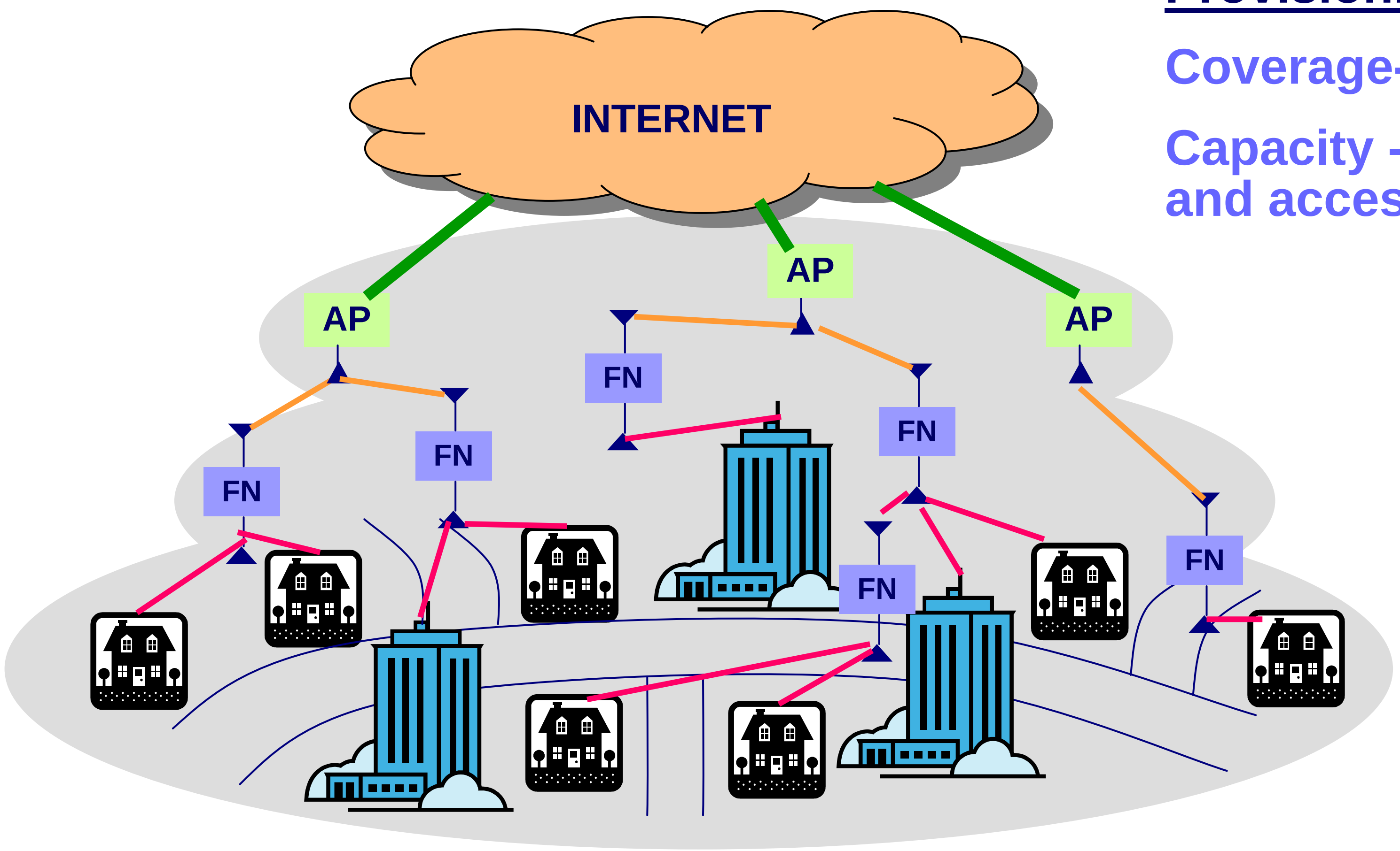


FN



MN

Model for Urban Deployment



Provisioning

Coverage- FNs

Capacity - APs and access links

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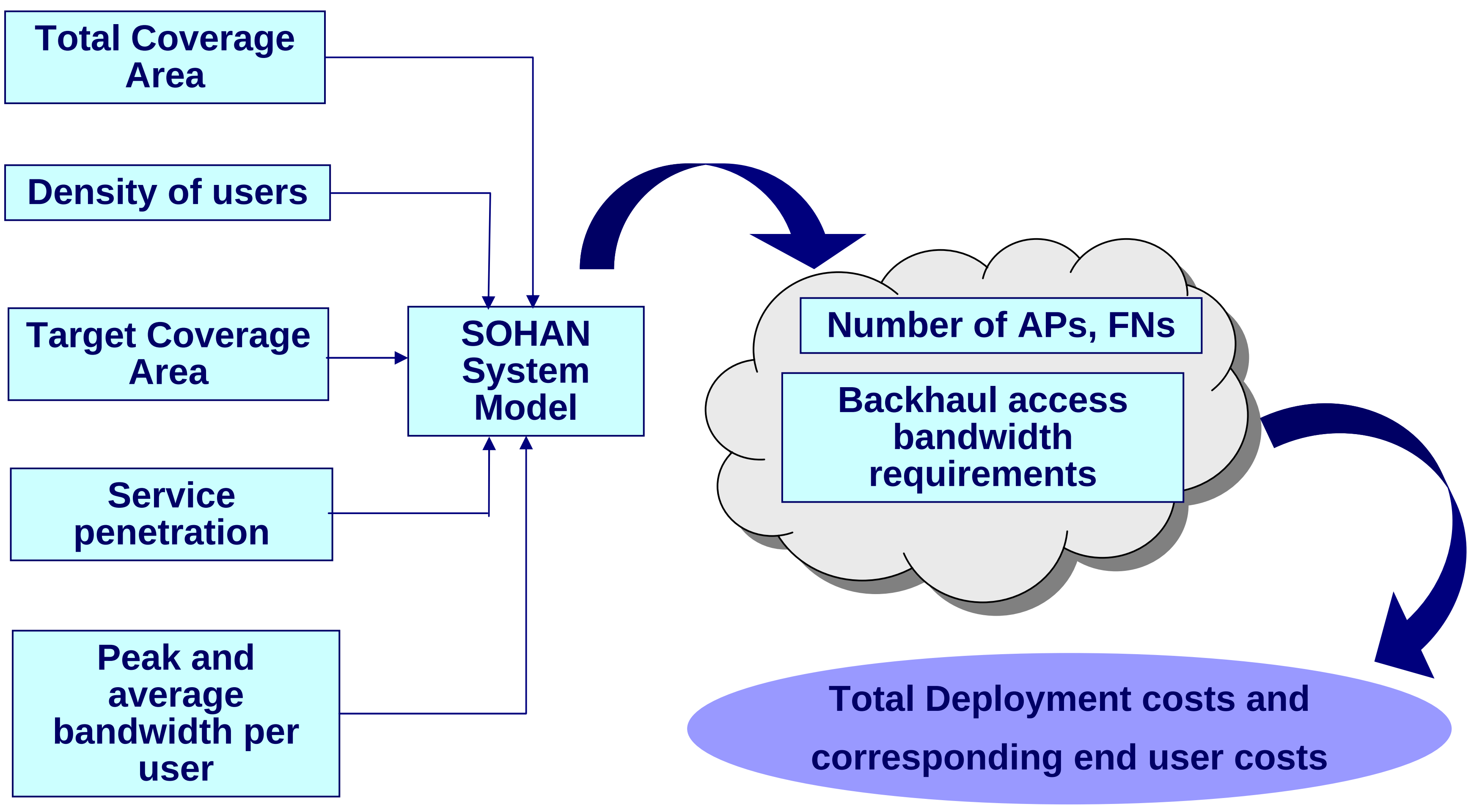
Model for Urban Deployment



Parameters

Coverage area	**2.5 km × 2.5 km = 6.25 sq km.**
Typical outdoor coverage 802.11b/g FN/AP	**~250 meters**
User Density per sq km[1]	**250**
Service penetration	**10 - 50 %**
Desired coverage	**~75%**
Average/peak bandwidth per user[2]	**15 Kbps, 50 Kbps**
Average number of users in the system = Density of population × Coverage Area × Service Penetration	**250×6.25×0.1 ~ 156 (10% penetration)** **250×6.25×0.5 ~ 780 (50% penetration)**
Average system bandwidth required	**156×15 Kbps = 2.34 Mbps (10% penetration)** **780× 15Kbps = 11.7 Mbps (50% penetration)**
Peak system bandwidth requirement	**156 × 50 Kbps = 7.8 Mbps (10% penetration)** **780 × 50 Kbps = 39 Mbps (50% penetration)**

[1] **Based on reports from Census 2001, http://www.mapsofindia.com/census2001/populationdensity.htm**

[2] **A. Balachandran, G. Voelker, P. Bahl, and V. Rangan, "Characterizing User Behavior and Network Performance in a Public Wireless LAN", *ACM SIGMETRICS'02*, Marina Del Rey, June 2002**

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System Model

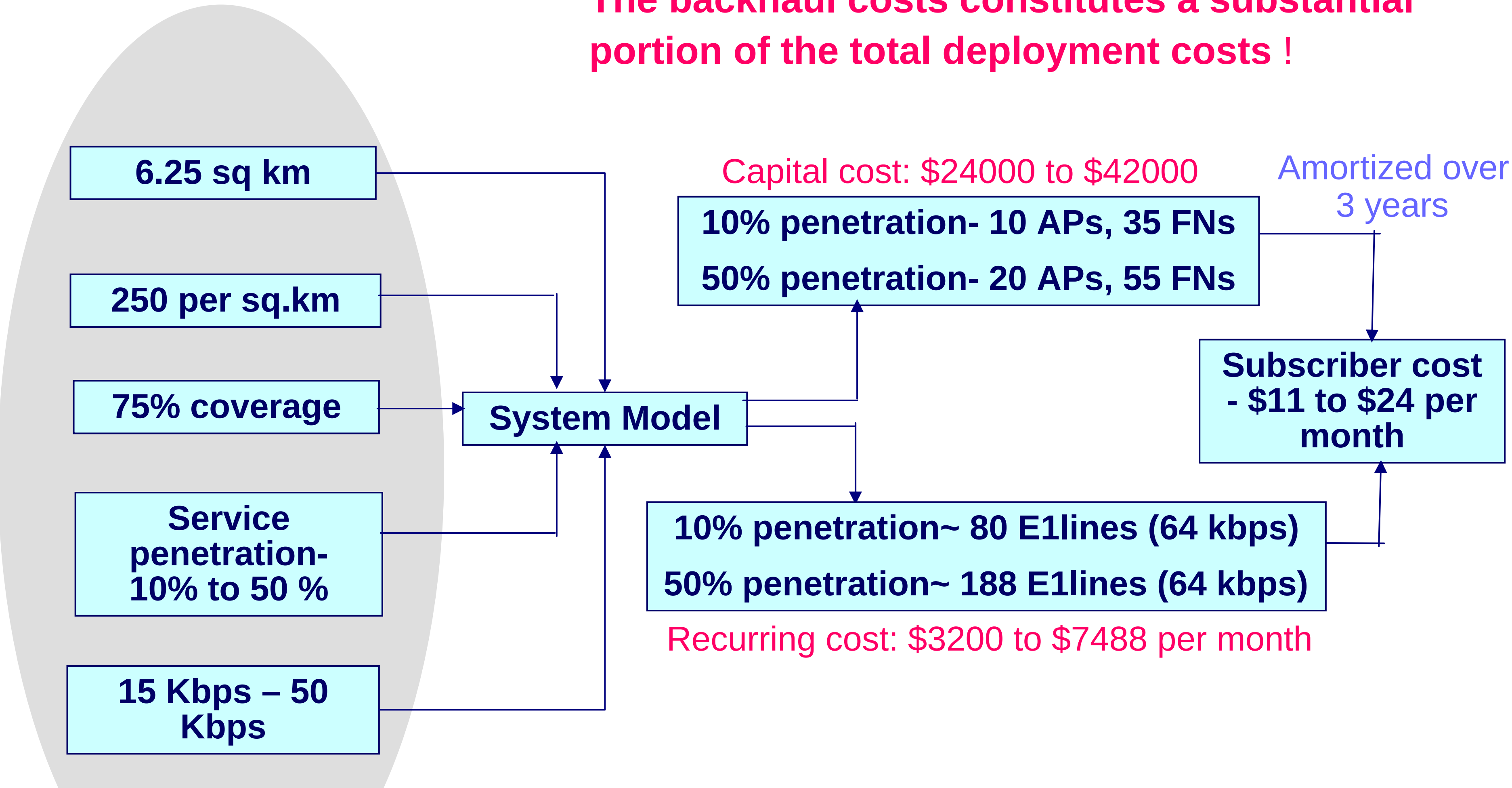
- **Coverage area with *n* uniformly distributed users (*n = 156 or 780 corresponding to 10% to 50% service penetration)***
- **Introduce FNs uniformly until 75% of the users are in range of at least one FN and the average number of users per FN is ~ 10-12**
- **Introduce *m* AP's where *m~ k*sqrt(#FN)***
- **Provision enough access links to support user traffic requirements**

B. Liu, Z. Liu, and D. Towsley, "On the capacity of hybrid wireless networks," *IEEE INFOCOM 2003,* March 2003

Suli Zhao, Ivan Seskar, and Dipankar Raychaudhuri, "Performance and Scalability of Self-Organizing Hierarchical Ad Hoc Wireless Networks", *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC 2004)*, March 2004

System Model: Summary

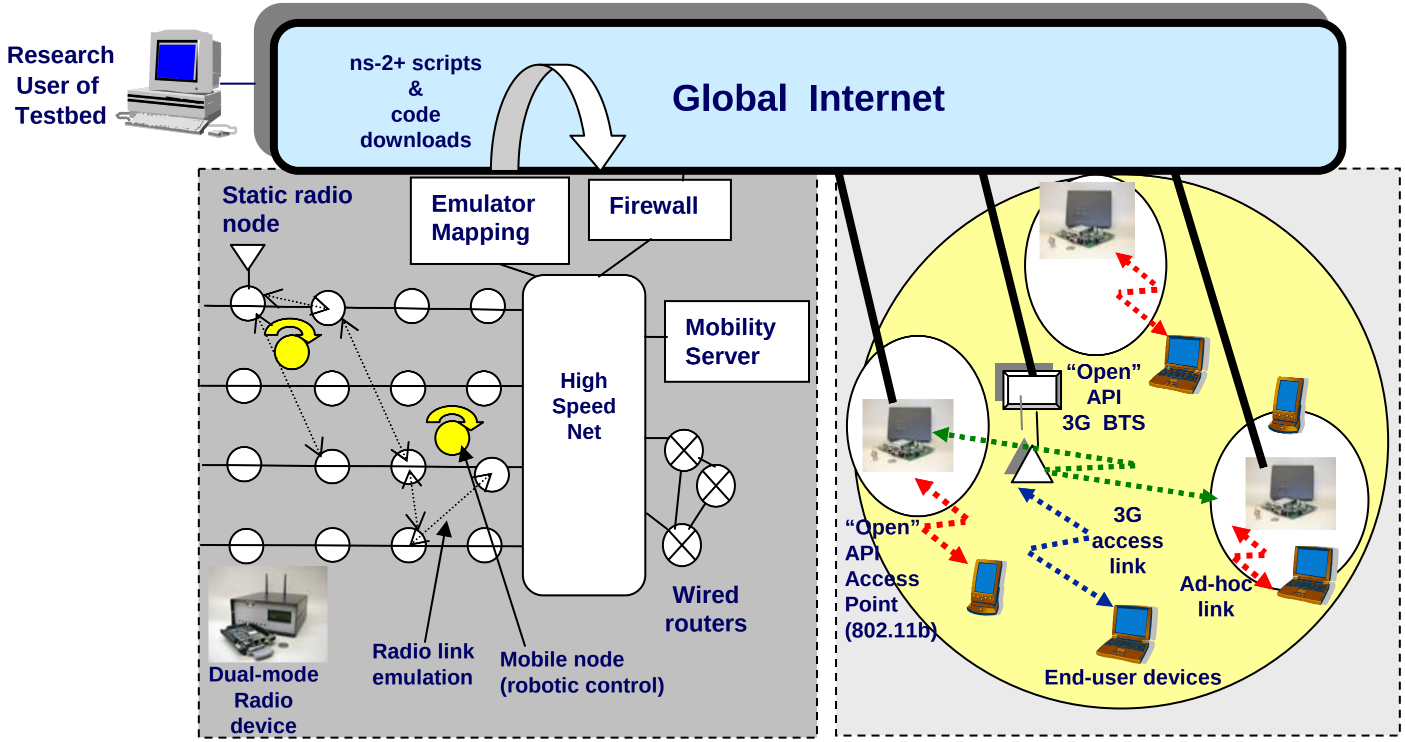
The backhaul costs constitutes a substantial portion of the total deployment costs !



Leasing Costs are based on "Consultation Paper on Revision of Ceiling Tariff for Domestic Leased Circuits", http://www.trai.gov.in/cpaper22.htm

Experimental Evaluation on ORBIT Testbed

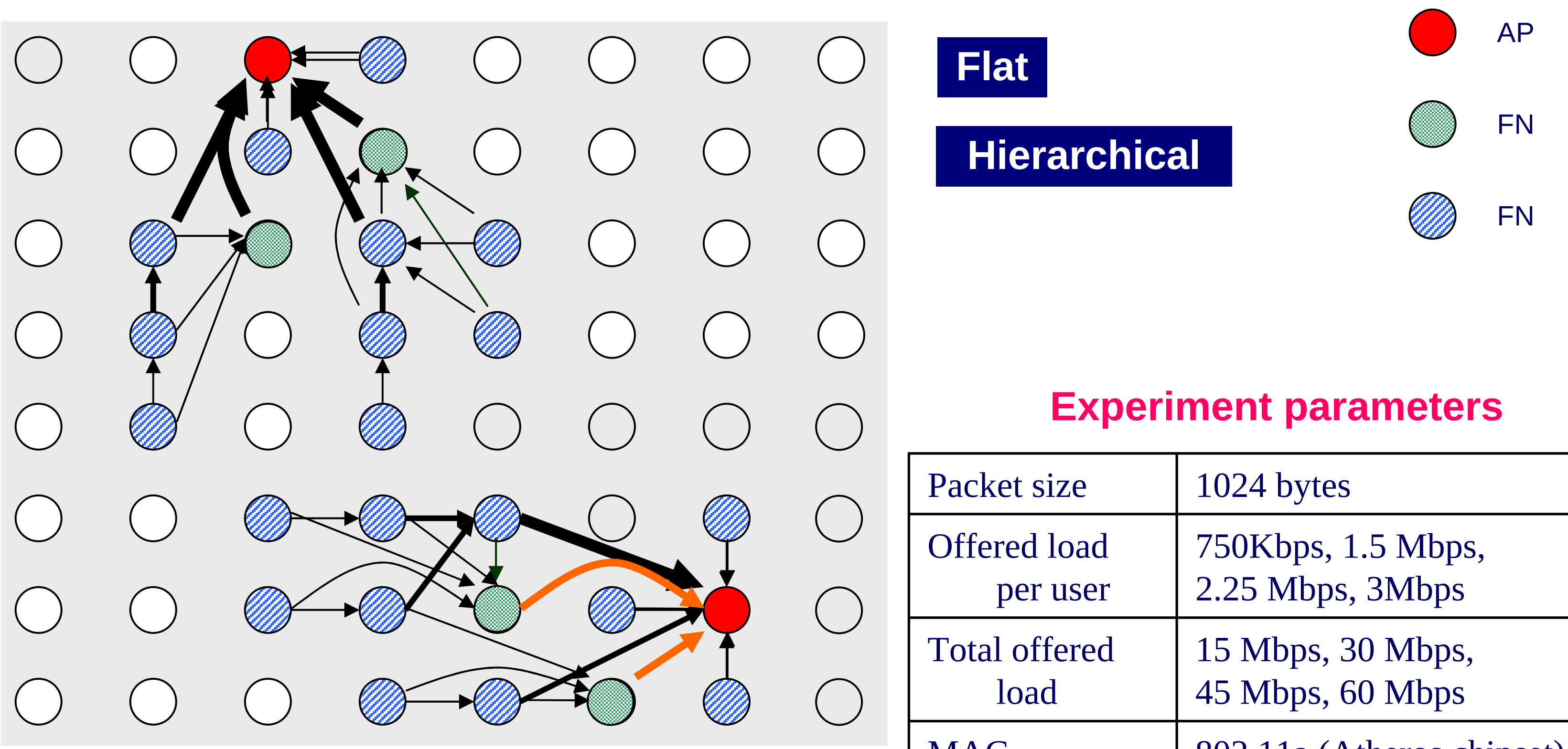
- NSF program ("NRT") aimed at establishing a number of open-access network research testbeds, both wired and wireless
- WINLAB (along with Columbia, Princeton and industry partners) currently developing an open-architecture wireless testbed with focus on 4G protocols



1. Radio Grid for Lab Emulation

2. Field Trial Network

Experimental evaluation



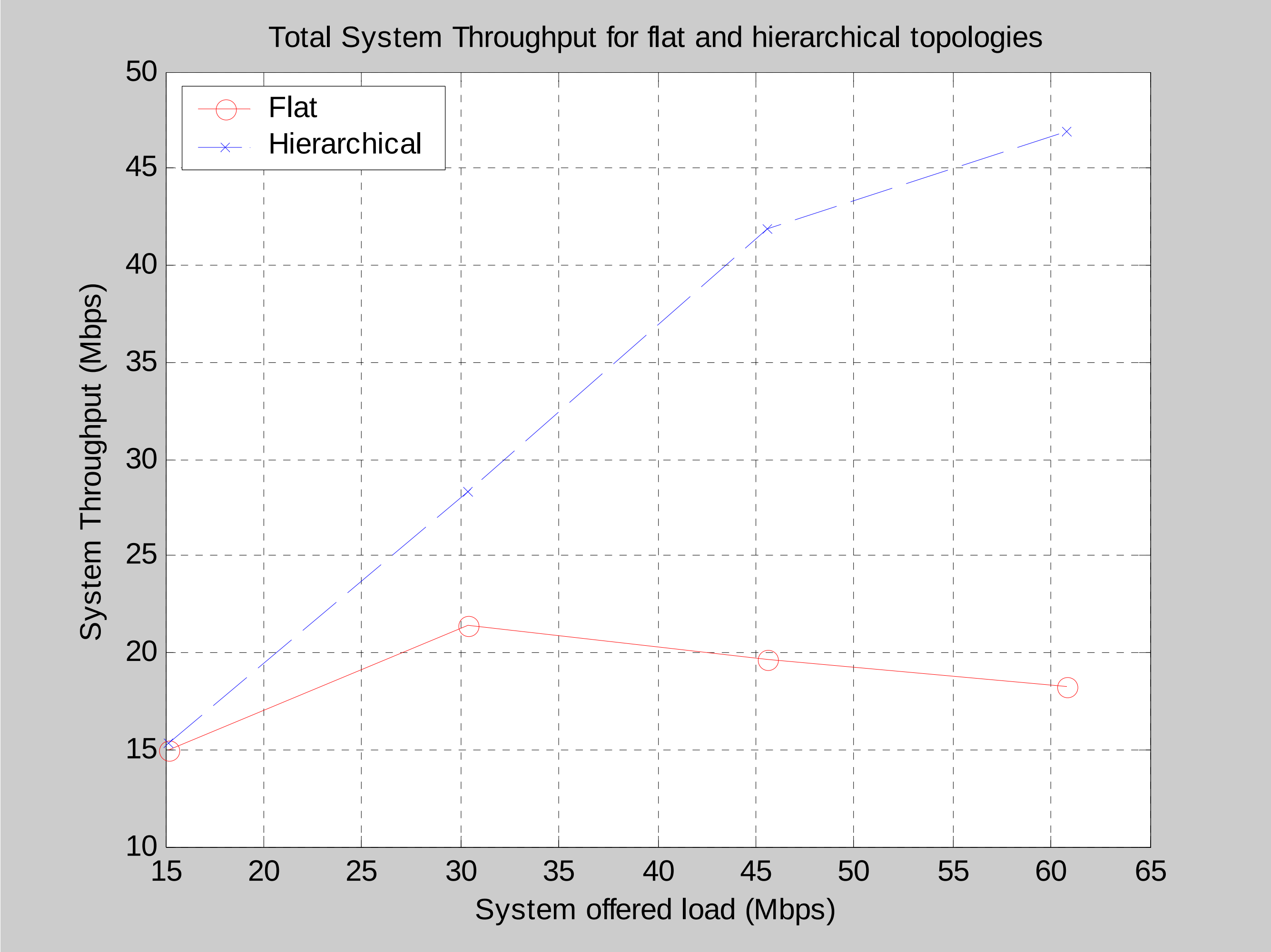
Scaled area considered (0.9 sq. km, 20 users, 4 FNs, 2 APs)

Experiment parameters

Packet size	1024 bytes
Offered load per user	750Kbps, 1.5 Mbps, 2.25 Mbps, 3Mbps
Total offered load	15 Mbps, 30 Mbps, 45 Mbps, 60 Mbps
MAC	802.11a (Atheros chipset)
Flat topology Hierarchical topology	AP1 on channel 40 (5.2 Ghz) AP2 on channel 56 (5.28 Ghz) AP1-FN1,2 channel 40 (5.2 Ghz) FN1,2-MN channel 64 (5.32 Ghz) AP2-FN3,4 channel 56 (5.28 Ghz) FN3,4-MN channel 48 (5.24 Ghz)

System Performance on ORBIT

System Throughput



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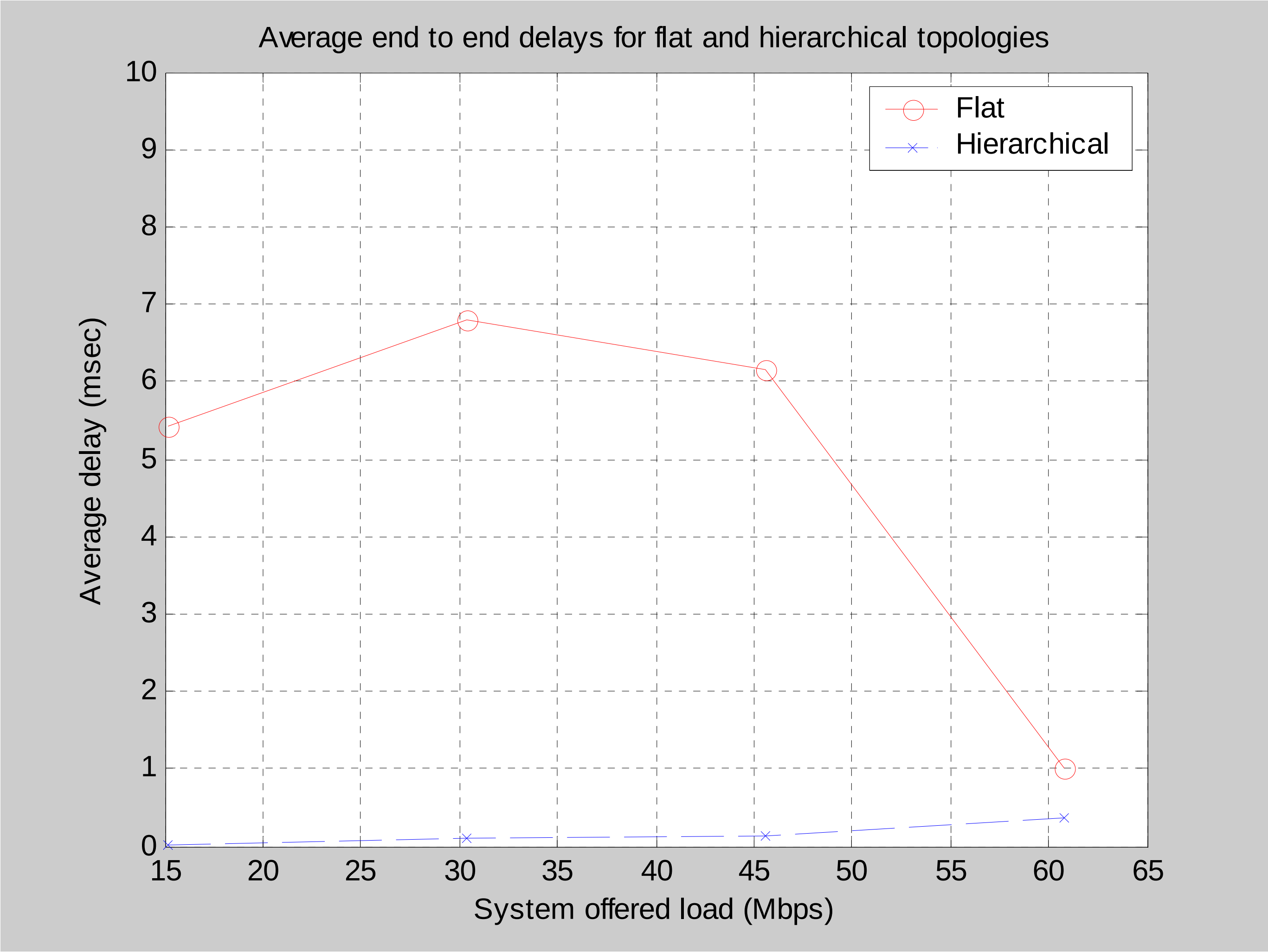
System Performance on ORBIT

Average end-to-end delay



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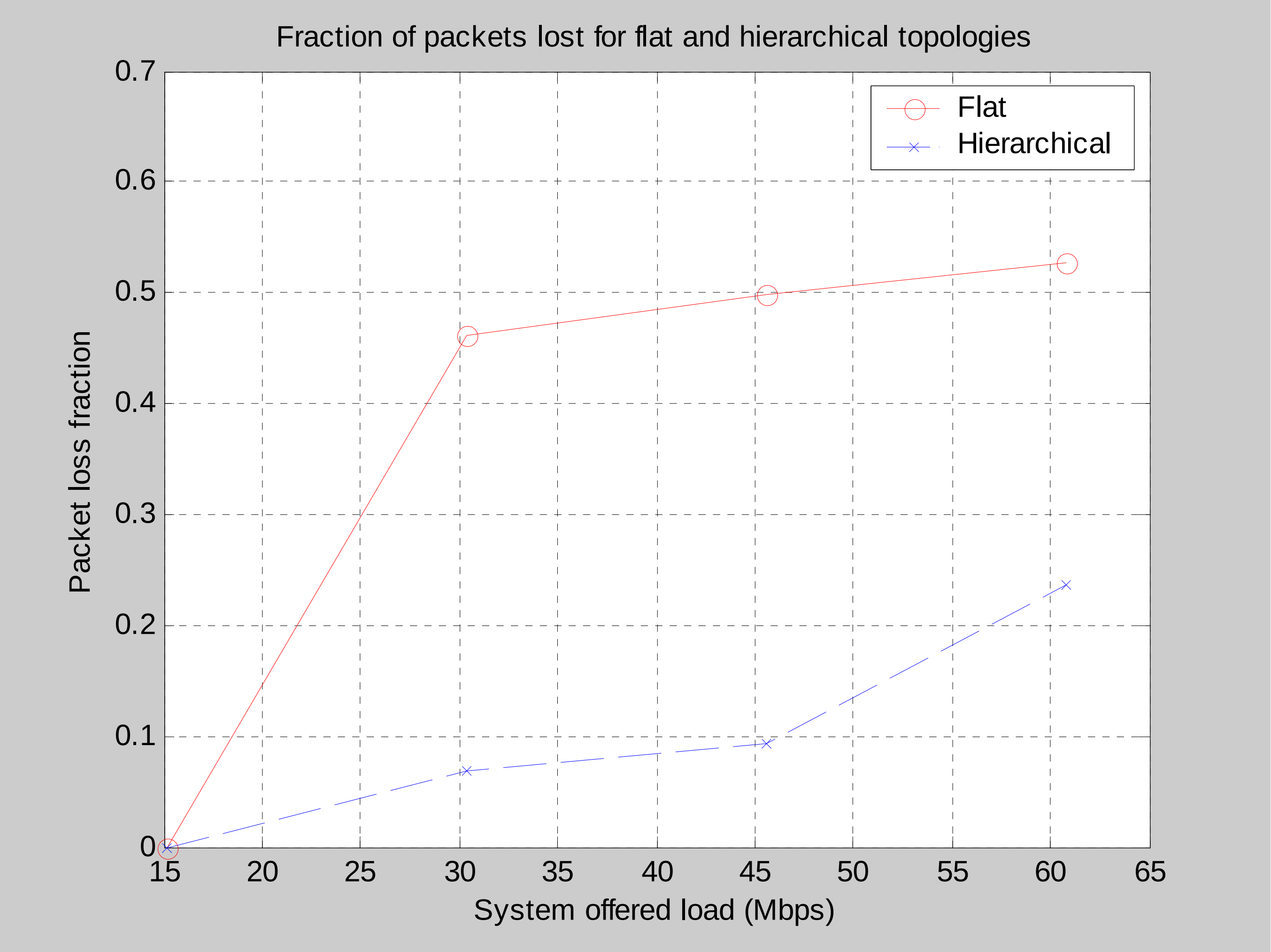
System Performance on ORBIT

Packet loss



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Summary of results

	Hotspot	Hierarchical Mesh	802.16[1] (projected)
Number of APs (or basestations)	75	20	1
Number of FNs	0	55	0
Data Density (Mbps/sq. km)	~80	~50	~4
End user equipment cost (NIC or 802.16 roof mounted unit)	$50	$50	~$300
Capital cost (APs, FNs, 802.16 base stations + associated eq.)	$75K	$42K	$100K
Recurrent cost (access links)	$12K p.m	$7488 p.m.	$10K
Monthly Subscription cost (amortized over a period of three years)	~$20	~$11	??

[1]**WiMax Forum**

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Concluding Remarks

- Hierarchical mesh architecture provides significant capacity and QoS improvements over conventional flat mesh
- "SOHAN" system prototype developed and validated at WINLAB – candidate technology for metro-area mesh
- Results show that system can scale well and meet capacity/cost needs for medium-density urban scenario
- Achieves ~50 Mbps/ sq km at a cost of ~$11-25 per subscriber per month, comparing quite favorably with alternatives such as 802.16 or hot-spot WLANs

Future Work, References

- Improve protocol performance using cross-layer (integrated PHY, MAC, routing) methods
- Conduct outdoor field trials on ORBIT testbed during 2005-06

S. Ganu, L. Raju, B. Anepu, I. Seskar, D. Raychaudhuri, "Architecture and Prototyping of an 802.11-based Self-Organizing Hierarchical Ad-Hoc Wireless Network (SOHAN)", Proceedings of the International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2004), Barcelona, Sep 2004

L. Raju, S.Ganu, B. Anepu, I. Seskar and D. Raychaudhuri ,"BEacon Assisted Discovery Protocol (BEAD) for Self-Organizing Hierarchical Wireless Ad-Hoc Networks ", Proceedings of IEEE Global Telecommunications Conference (Globecom 2004), Dallas, Nov 2004

L. Raju, S.Ganu, B. Anepu, I. Seskar and D. Raychaudhuri "BOOST: A BOOtSTrapping Mechanism for Self-Organizing Hierarchical Wireless Ad hoc Networks", IEEE Sarnoff Symposium, Princeton, April 2004

S. Zhao, K. Tepe, I. Seskar and D. Raychaudhuri, “Routing protocols for self-organizing hierarchical ad-hoc wireless networks", *IEEE Sarnoff 2003 Symposium*, March 2003

S. Zhao, I. Seskar and D. Raychaudhuri, "Performance and Scalability of Self-Organizing Hierarchical Ad Hoc Wireless Networks", *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC 2004),* Atlanta, GA

ORBIT Testbed (Jan 2005)

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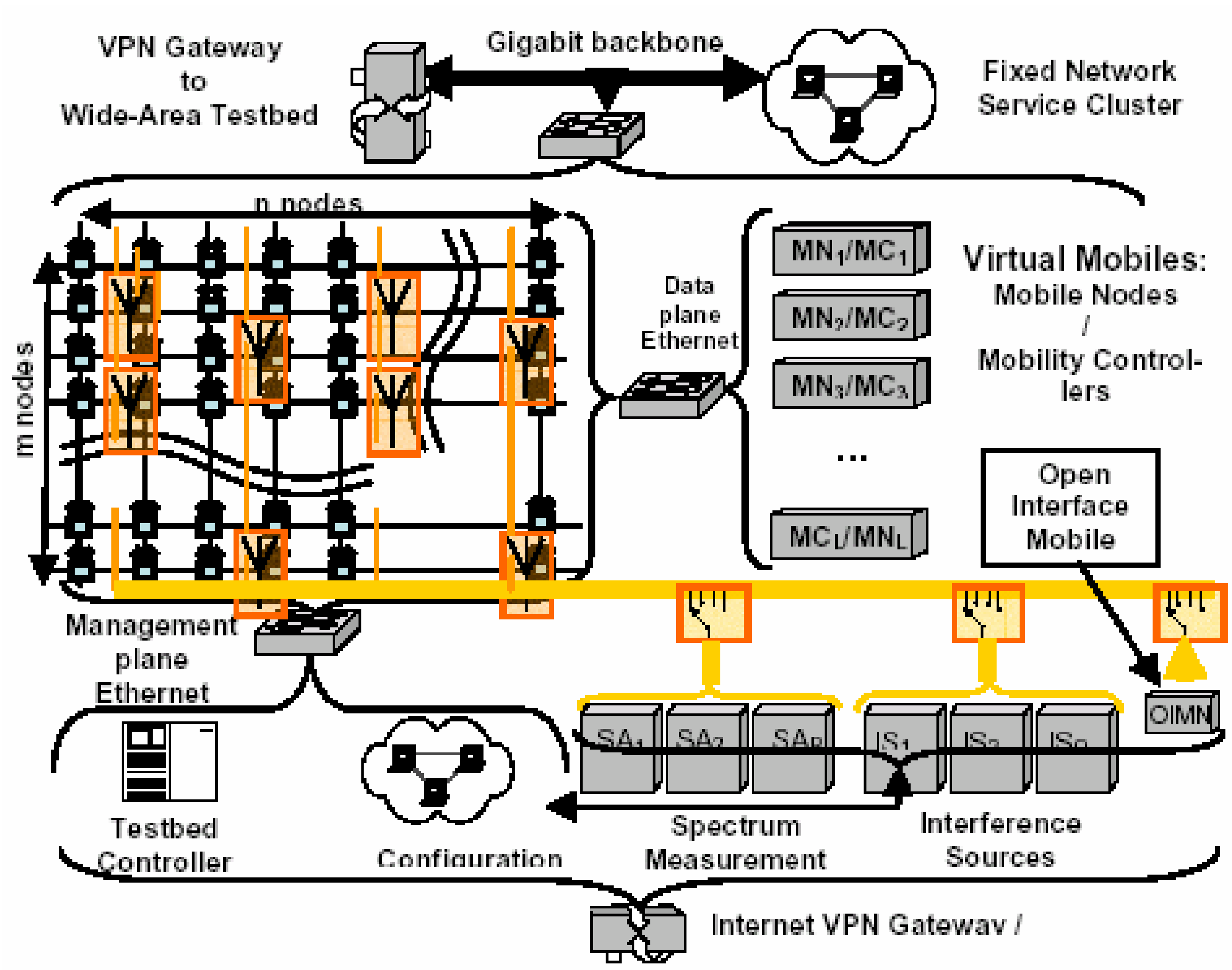
ORBIT: Radio Grid



Cost calculation

10% service penetration

Item	Unit Price	Total Price
10 Access Points	~$1000	$10000
35 FN	~$400	$14000
Total fixed costs		$24000

Fixed costs

Item	Unit Price (per month)	Total Price
80 leased lines (64 Kbps each)	(Rs 24000 p.a.)/(12 × 50) ~$40	$3200 per month

Recurrent costs

50% service penetration

Item	Unit Price	Total Price
20 Access Points	~$1000	$20000
55 FN	~$400	$22000
Total fixed costs		$42000

Fixed costs

Item	Unit Price (per month)	Total Price
188 leased lines (64 Kbps each)	(Rs 24000 p.a.)/(12 × 50) ~$40	$7488 per month

Recurrent costs

Costs amortized over three years over number of subscribers

10% - (24000 + 36 × 3200) = $139200 / 160 ~ $24 per user per month

50% - (42000 + 36 × 7488) = $311568 / 780 ~ $11 per user per month

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