# Scatternet formation algorithms for multihop Bluetooth networks

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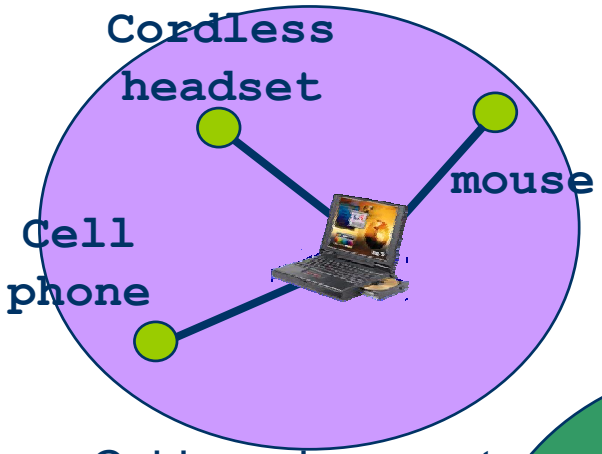
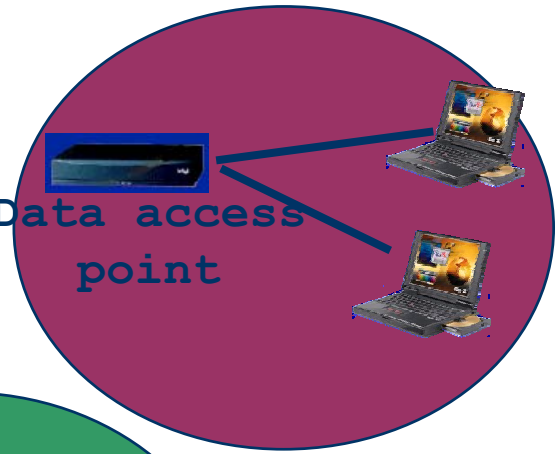
# Bluetooth (BT) History

- Named after a Danish Viking King who unified and controlled Denmark and Norway
  - → BT aims at unifying telecom. and computing industries
- First standard release in 1999 (v 1.0)
- BT Special Interest Group counts over 1800 members, including Ericsson,Nokia, IBM, Intel, Toshiba,Microsoft, Lucent, 3Com, Motorola...
- All BT SIG members agree to provide key technologies for development, have BT license and BT brand for free

# Bluetooth Application Scenarios




Cable replacement




Internet access

**Ad hoc networking**

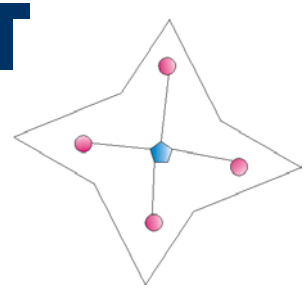
# Bluetooth Technology (BT): Enabling Ad Hoc Networks

- Wireless technology in the 2.4GHz, globally available, license free ISM (Industrial, Scientific and Medical) band, originally introduced for cable replacement → must be low cost, reliable
- 1MHz spaced channels, GFSK modulation → 1Mb/s
- Frequency Hopping Spread Spectrum
  - Devices follow a FHSS sequence
  - Frequency used for transmission changes for every packet

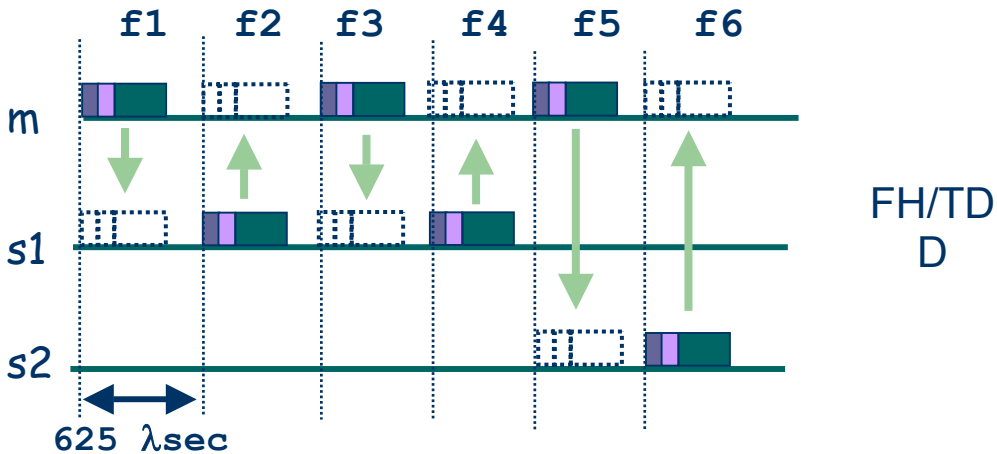
  ↓

  low interference, security
- Time divided in slots (1 slot = 625 μs)
- Packet size: 1, 3 or 5 slots
- Short range communication (10 - 100 m)

# Bluetooth: Piconets

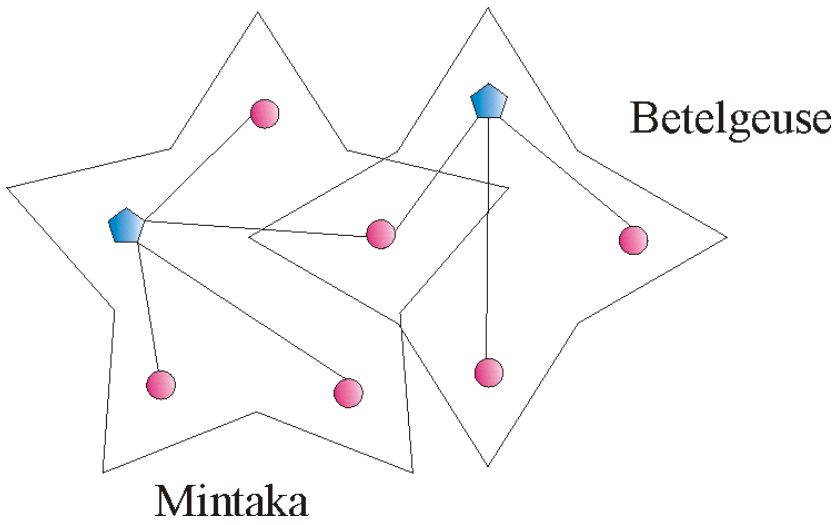


- **BT devices are organized in *piconets*, clusters of :**
  - One master
  - Multiple slaves, no more than 7 actively communicating
- **Synchronization based on master ID and clock**
  - Based on the master ID and clock a frequency hopping sequence is computed → all devices in a piconet use the same sequence
- **Master (M) – Slave (S) communication**



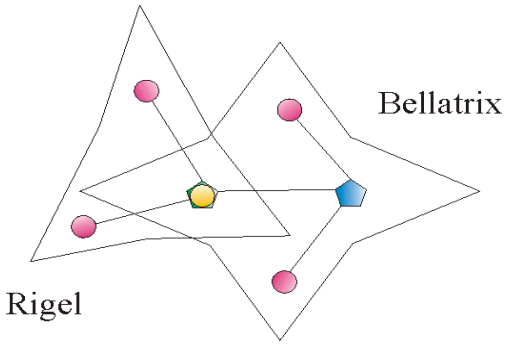

FH/TDD

# Bluetooth: Scatternets

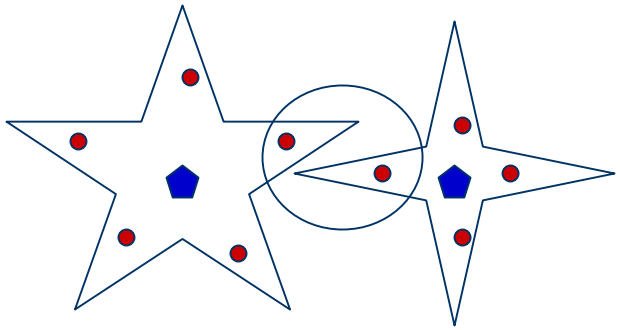



- Nodes can have multiple roles
- Nodes with multiple roles timeshare between multiple piconets
- A **scatternet** enables multi-hop communication

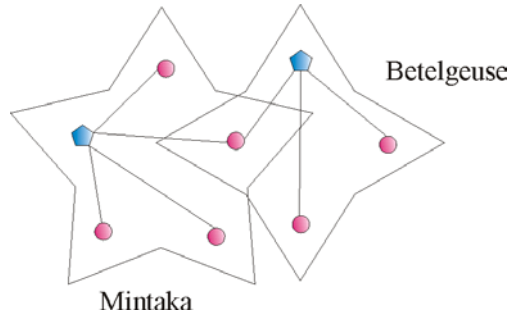
# Piconets Interconnection




master/slave



additional piconet interconnecting neighbor slaves



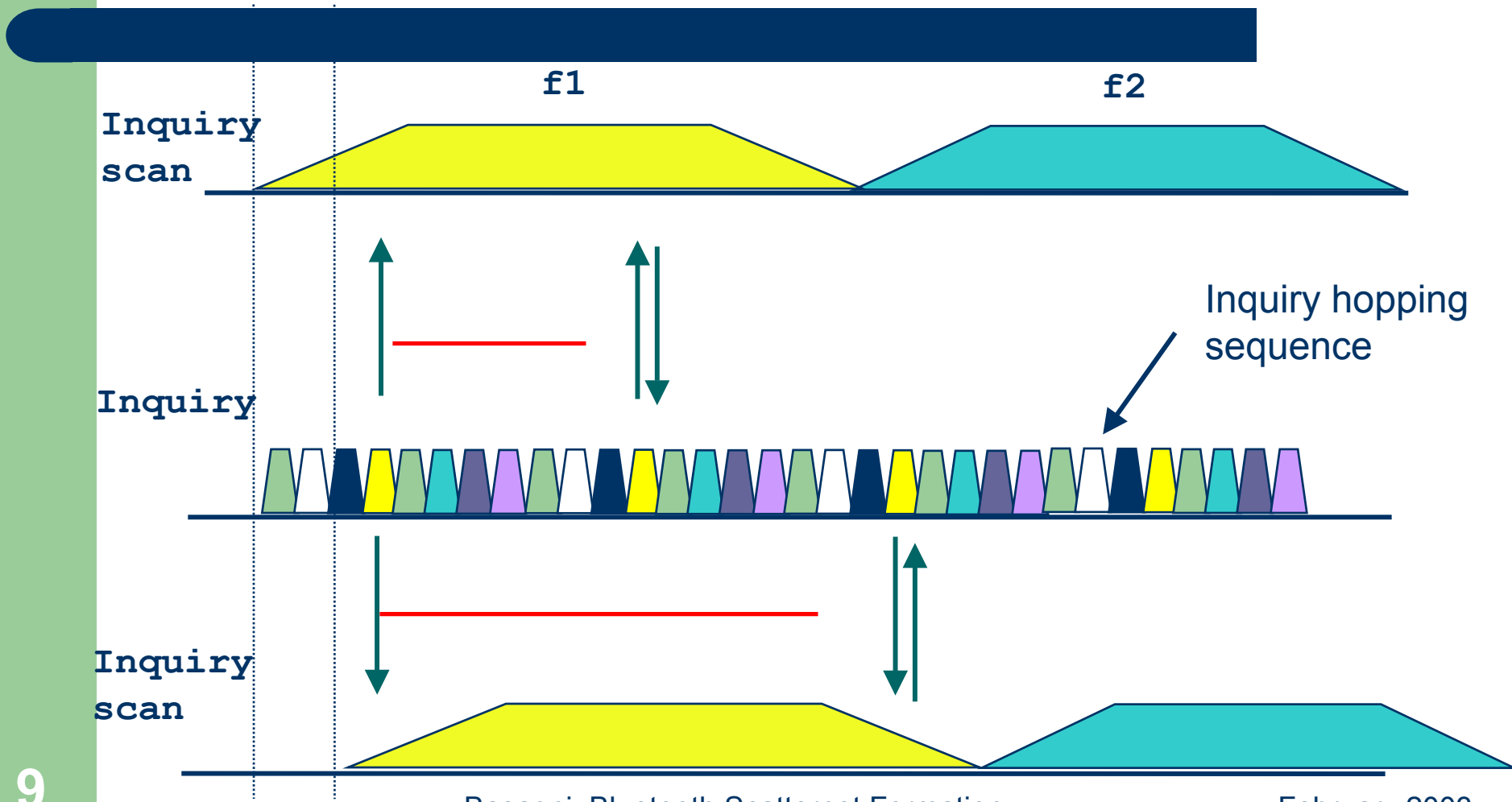

common slave

Efficiency

# Scatternet Formation

- Forming connected ad hoc networks of Bluetooth device
- Three major problems:
  - Device discovery → use BT standard inquiry and paging procedures
  - Piconet formation → use BT standard inquiry and paging procedures
  - Piconet interconnection

# Inquiry procedure



# Device discovery in BT standard

- Requires neighbor nodes to be in opposite modes (inquiry/inquiry scan)
- Leads to asymmetric neighbor discovery
  - The inquirer gather information on the neighbor BT clock and address, not viceversa

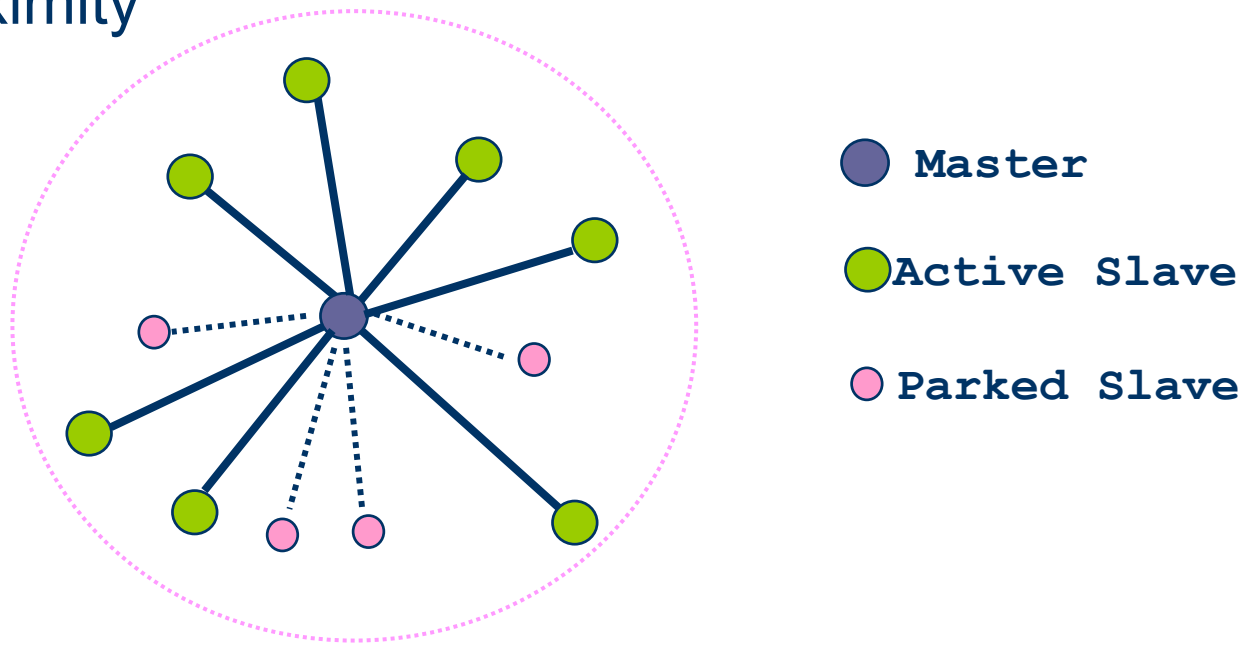
# Symmetric device discovery

First proposed by Salonidis,Tassiulas, Baghwat, INFOCOM 2001

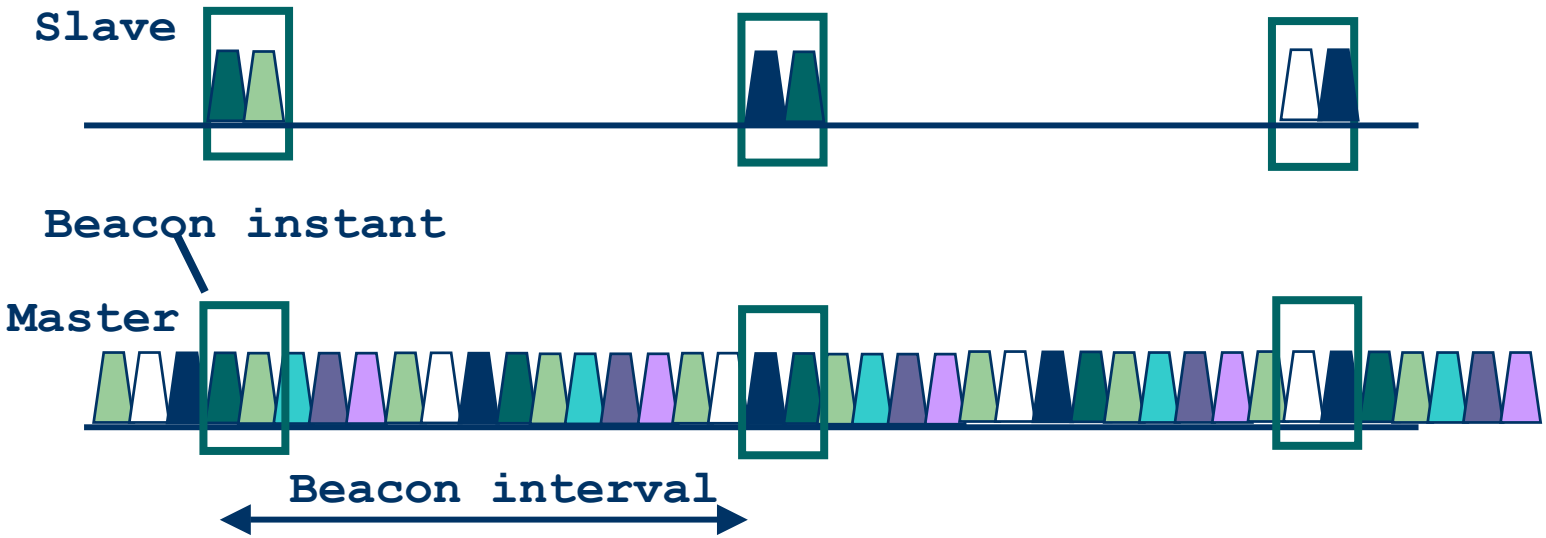
- Nodes alternate between inquiry and inquiry scan mode
- Random residence times in a mode
- Nodes perform standard inquiry (inquiry scan) procedures when in inquiry (inquiry scan) mode
- Idea: “two nodes discover each other when they are in opposite mode for sufficiently long time”

# Piconet formation

- Page - scan protocol
  - to establish links with nodes in proximity



# Low Power mode (Park)




- Power saving + keep more than 7 slaves in a piconet
- Give up active member address, yet maintain synchronization
- Communication via broadcast LMP messages

# Scatternet Formation: Previous Solutions

- Single-hop topologies (the radio vicinity of all nodes is required):
  - Salonidis et al.: works for up to 36 nodes
  - Law et al.: Creates a tree
  - Tan et al.: Creates a tree

# Scatternet formation: Previous Solutions

- Multi-hop topologies:
  - Zaruba et al.: BlueTrees, tree-like connected scatternet. Depends on a designated node
  - Haas et al.: BlueNets, mesh-like scatternet formation. Connectivity of the scatternet is not guaranteed.
  - Stojmenovic: mesh-like connected scatternet based on topology reduction techniques. Requires additional hardware (e.g., GPS receivers)

# BTCP (Bluetooth Topology Construction Protocol)

- Proposed by Salonidis et al., INFOCOM 2001
- Distributed leader election (device discovery)

  -Based on number of nodes that “won” so far

  -Every confrontation requires the exchange of all the FHS of associated nodes
- Centralized (at the leader) scatternet formation
- Target:min. # piconets, piconet per gw, connected scatternet
- Limits: Single-hop, <= 36 nodes

# Law, Siu solution

- MobiHoc, Globecom 2001
- low #piconets, low.max degree, low network diameter
- Randomized protocol

  -proceeds in rounds

  -in each round ‘components’ are merged

  -the leader of each component goes to inquiry/inquiry scan with a given probability

  -components discoverying each other merge

# TSF (Tree Scatternet Formation)

- All nodes are originally free nodes
- Free nodes can aggregate in a tree with each other or connect to tree nodes
- Generated trees are made of 1 root node, 1 coordinator and several tree nodes
- Different trees discover each other through the coordinators and merge through the roots
- Target: self-healing
- Limits: single-hop, tree topology, no guarantee <= 7 slaves

# BlueTrees

- protocol initiated by a ‘designated root’ which becomes master and selects neighbors which do not belong to a piconet as slaves
- slaves assume a master role and the procedure iterates

- proposal of solutions to keep the number of slaves per piconet below 7 and do not need to rely on a designated node

Major limit: generates a tree

# BlueNet

- Each node randomly enters either page or page scan. Master nodes selects up to $N_{max}$ of their neighbors as slaves.
- Isolated nodes become masters and selects up to $N_{max}$ neighbor as slaves.
- Piconet interconnection through common slaves.

Major limit: no guaranteed connectivity

# Stojmenovic solution

- Idea: graph manipulation so that nodes degree <= 7 and the nodes connectivity is maintained
- Every clustering applicable on the resulting topology
- Generates a mesh topology

Major limit: requires extra hardware (e.g., GPS)

# State of the Art in BT Scatternet Formation

| | Multihop | Topology | Comments |
|---|---|---|---|
| Salonid,Tassiulas, Bhagwat | NO | Mesh | <36 devices |
| Tan ,Balakrishnan et al. | NO | Tree | Self-healing |
| Law, Siu | NO | Tree | Random algorithm |
| Zaruba, Basagni, Chlamtac | YES | Tree | Requires an initiator device |
| **BlueStars**<br>**BlueMesh** | **YES**<br>**YES** | **Mesh**<br>**Mesh** | **network connectivity**<br>**Guaranteed <7 slaves,** |
| Stojmenovic | YES | Mesh | Requires additional HW |
| Haas et al. | YES | Mesh | No guaranteed connectivity |

# BlueStars: Mesh-like Connected Scatternet

- Distributed solution: all nodes participate to the formation with minimal, local topology knowledge (one-hop neighbors)
- Multi-hop solution: nodes need not to be in each other communication range
- Mesh-like solution: multiple routes between pair of nodes
- No additional hardware is required
- Guaranteed connectivity

# BlueStars: Three-phase Protocol

1. **Device discovery**: each nodes becomes aware of its one-hop neighbors and of their “weight” (symmetric knowledge)
2. **Piconet formation**: nodes are partitioned into groups each with one master and possibly multiple slaves
3. **Piconet interconnection**: piconets whose masters are at most three hops away are interconnected to form a connected scatternet

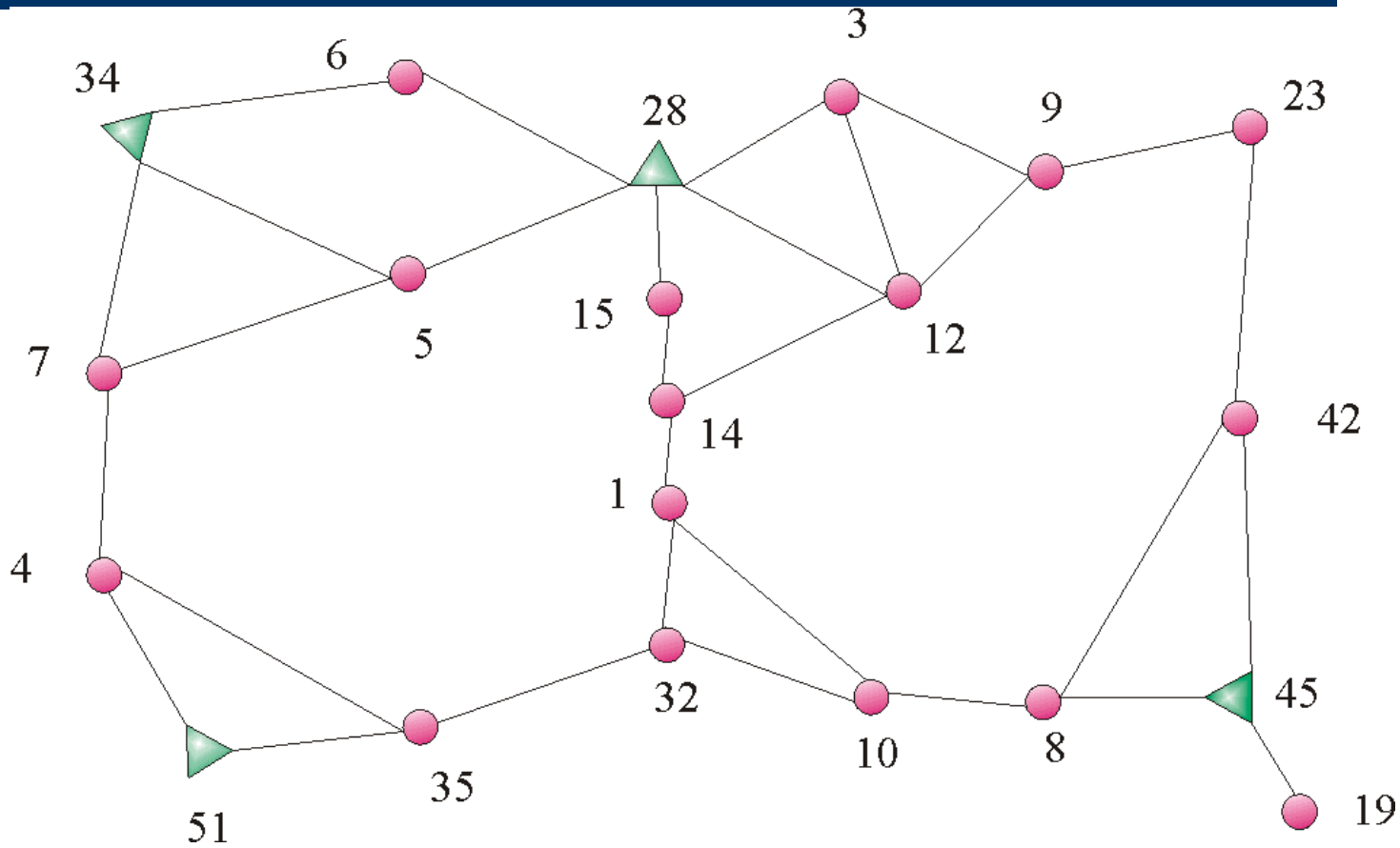
# BlueStars: Device Discovery

- Uses the *inquiry* and *paging* procedures described in the BT specification [Salonidis+00]
- Each node alternates between *inquiry* and *inquiry scan* mode (random durations)
- In order to ensure symmetric neighbor knowledge temporary piconets are set up for data (ID, weight, etc.) exchange

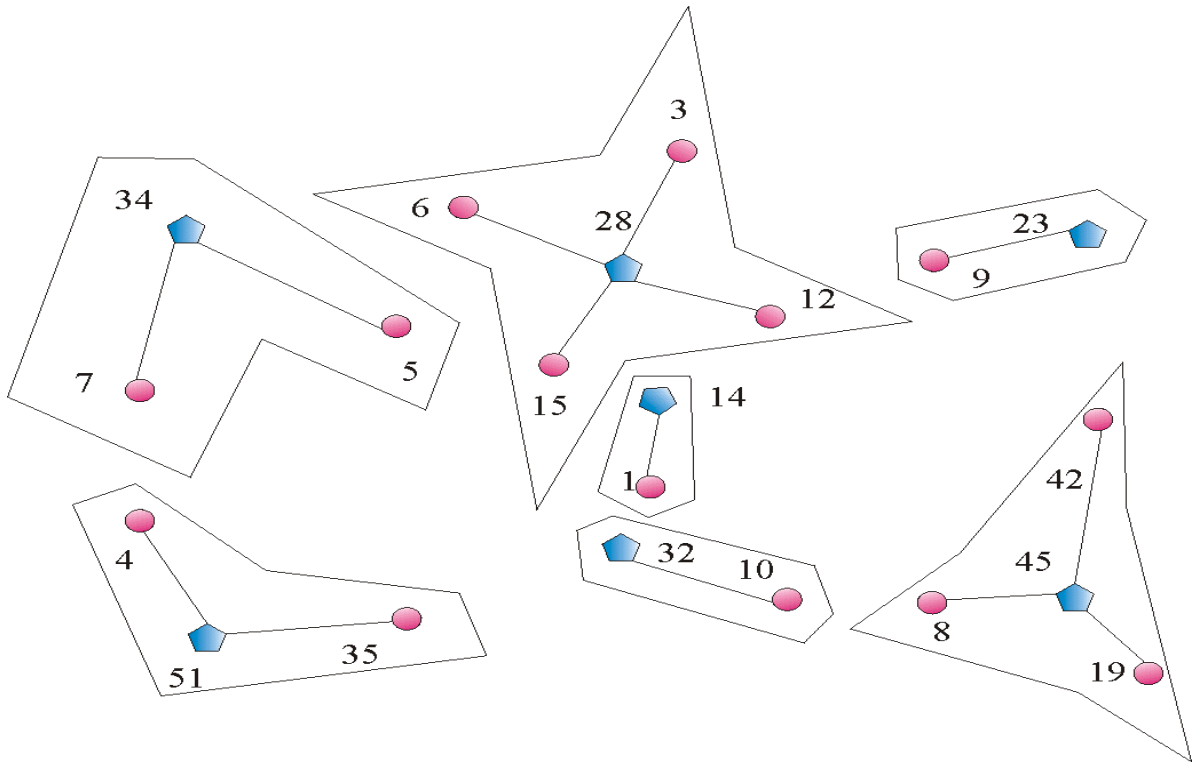
# BlueStars: Piconet Formation

- Nodes with the biggest weight in their neighborhood (init nodes) start the process
- Init nodes go to page mode, non-init nodes go to page scan mode
- Every node decide whether to be a master or a slave depending on the role of “bigger nodes”
- Slaves join the first master that pages them

# BlueStar: Piconet Formation



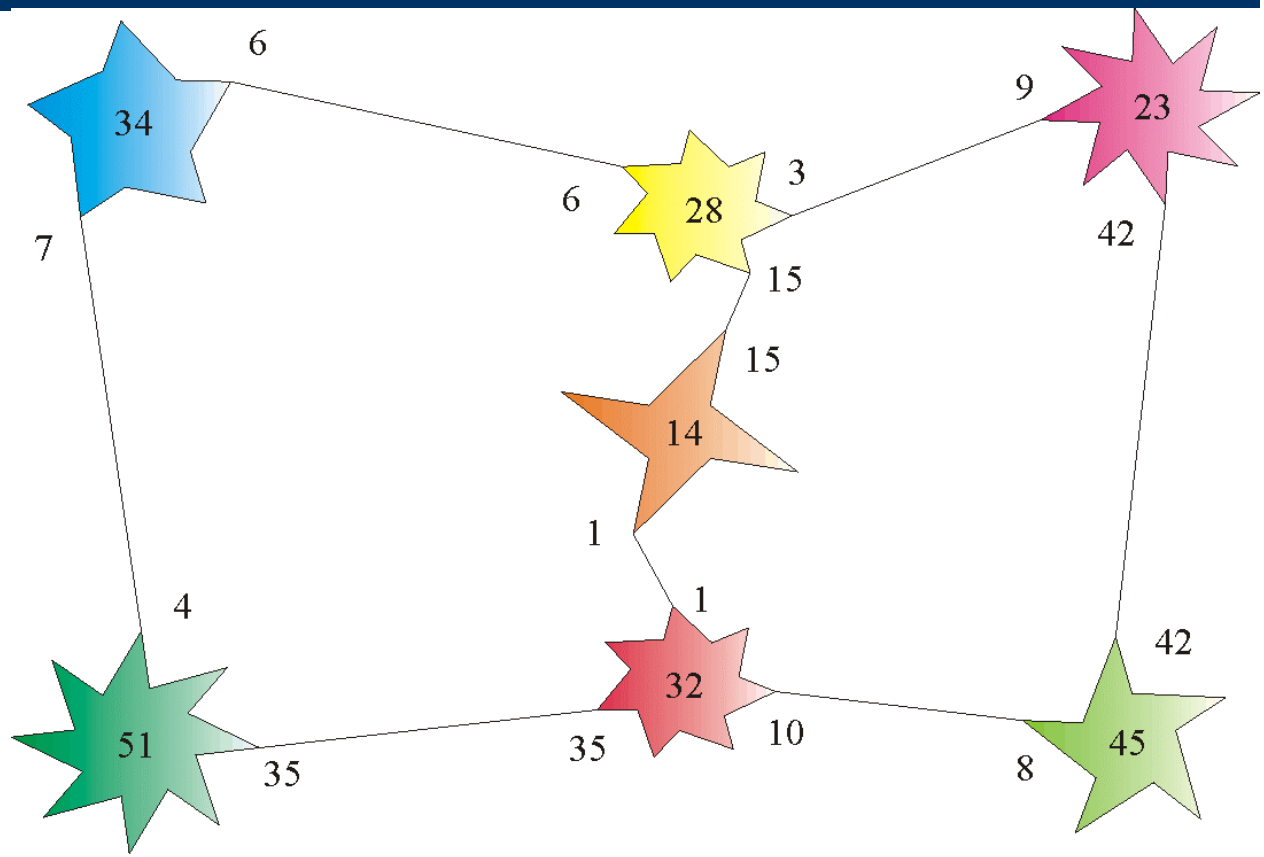
# BlueStars: Piconet Formation



# BlueStars: Piconet Interconnection

- Connectivity is guaranteed by finding routes between all masters at most three hops away [Chlamtac et al., 1999]
- Masters at most three hops apart are said M-neighbors
- “Init masters” start the process: common slaves and neighboring slaves are uniquely selected to interconnect M-neighbor

# BlueStars: Piconet Interconnection



# BlueStars: potential limits

- Time needed for device discovery

  → discovery of **all** neighbors may be time consuming when nodes degree is high BUT it is not needed! (Basagni, Bruno, Petrioli, Networking 2002)

- Piconets may have more than 7 slaves → potential need to park and unpark nodes for communication

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***BlueMesh***

# BlueMesh - idea

- Proceeds in iterations
- BT devices are divided into piconets, each piconet has at most 7 slaves
- each master selects <=7 slaves among its neighbors so that through them all the other neighbors can be reached
- adjacent piconets interconnection is achieved either through common slaves, or through neighbor slaves
- Only nodes which will be involved in extra piconets for sake of scatternet connectivity survive to the next iteration

# Performance evaluation

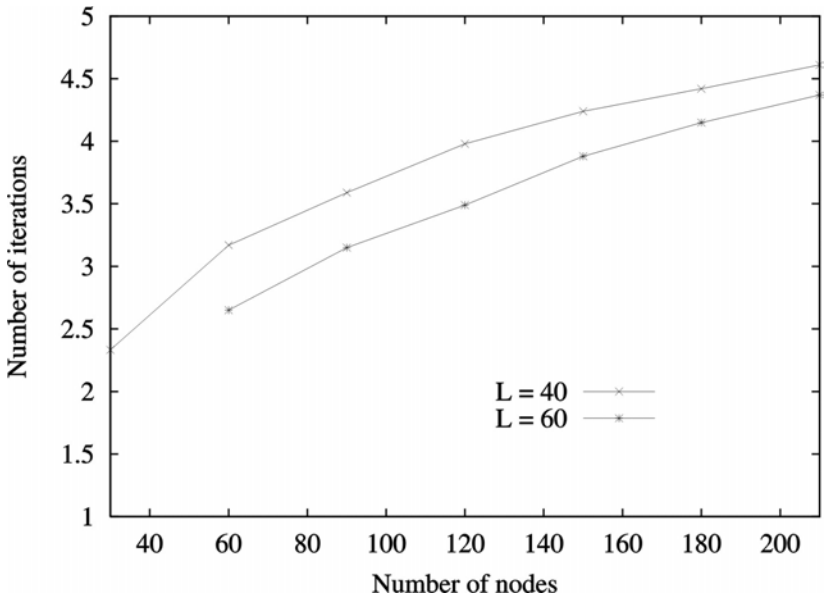
- <= 210 nodes, uniformly distributed in a square of side L=40, 60

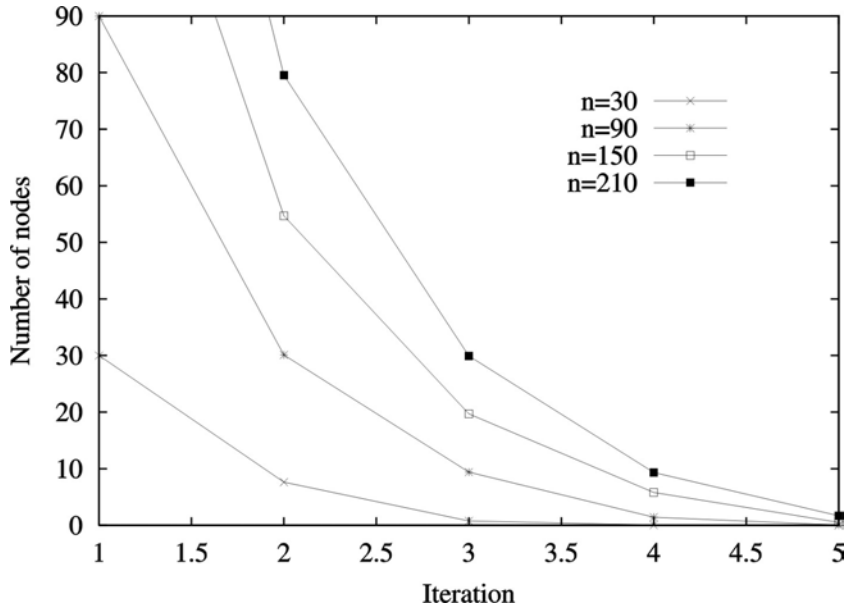
  *Avg. degree*

| # nodi | 30 | 60 | 90 | 120 | 150 | 180 | 210 |
|---|---|---|---|---|---|---|---|
| L=40 | 4.6 | 9.2 | 13.9 | 18.6 | 23.3 | 28 | 32.8 |
| L=60 | | 4.4 | 6.6 | 8.9 | 11.2 | 13.5 | 15.8 |

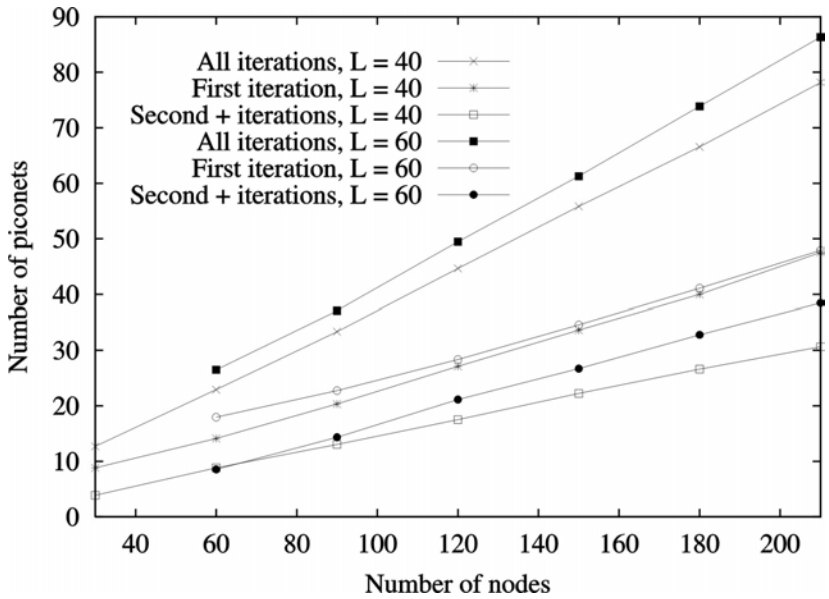
- Transmission range: 10 m
- Topology = unit disc graph
- Results refer to connected topologies
- Metrics: ‘set-up time’, number of piconets, number of roles per node, number of slaves per piconet, route length

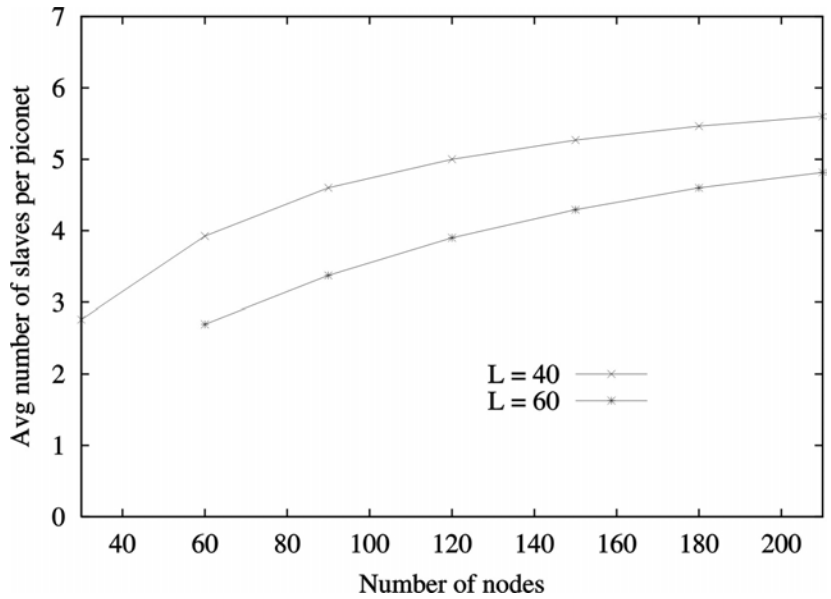
# BlueMesh – “set up time”



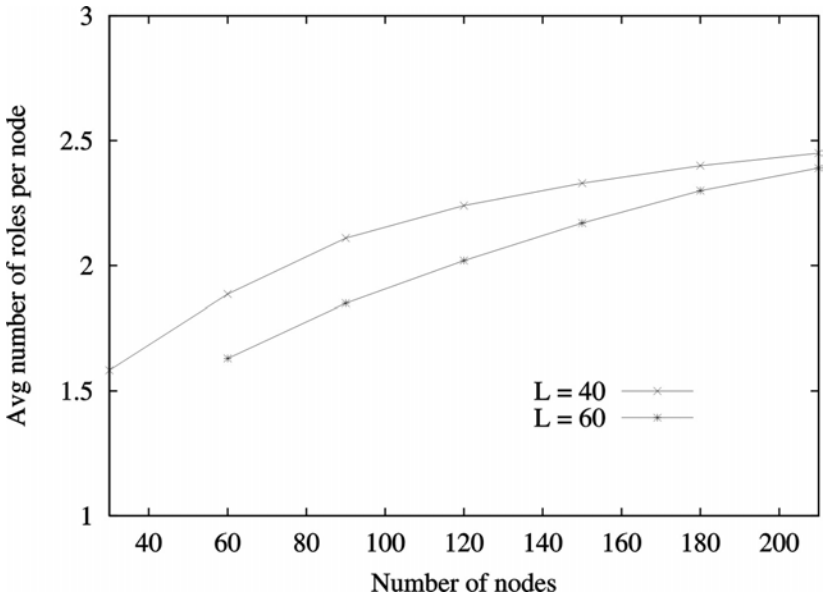



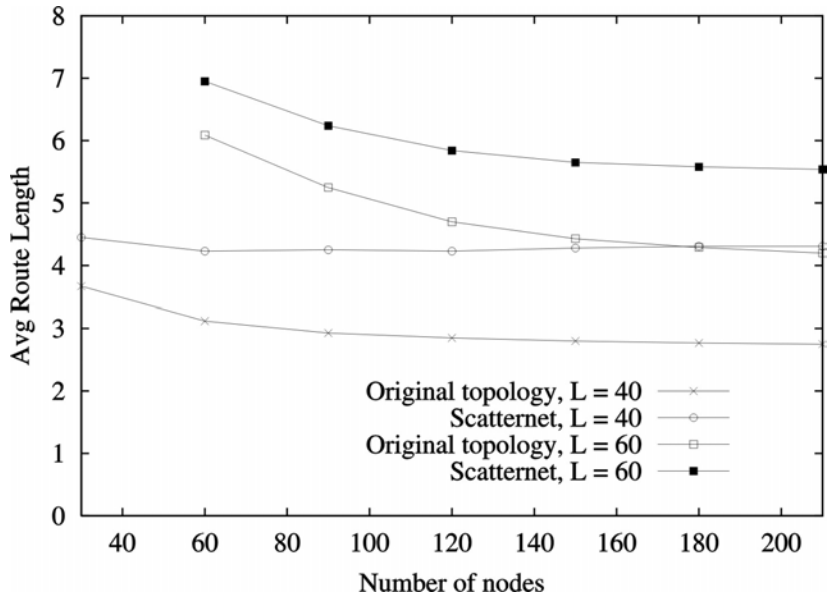
# BlueMesh - Results



# BlueMesh - Results



# Conclusions - 1

- BlueStars/BlueMesh are  distributed protocol for scatternet formation over multi-hop networks
- BT nodes do not need to be in radio vicinity
- The resulting scatternet is connected
- There are multiple routes between pairs of nodes (mesh-like topology)

# Conclusions - 2

- No additional hardware is necessary
- BlueMesh guarantees no more than 7 slaves per piconet
- Good performance

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2. Ching Law, Amar K. Mehta, and Kai-Yeung Siu. Performance of a new Bluetooth scatternet formation protocol. In Proceedings of the ACM Symposium on Mobile Ad Hoc Networking and Computing 2001, October 2001.
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4. Godfrey Tan, Allen Miu, John Guttag and Hari Balakrishnan. Forming Scatternets from Bluetooth Personal Area Networks. MIT Technical Report, MIT-LCS-TR-826, October 2001.

# Bibliography - multihop


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2. I. Stojmenovic, "Dominating set based Bluetooth scatternet formation with localized maintenance", Proc. Workshop on Advances in Parallel and Distributed Computational Models, at IEEE Parallel and Distributed Processing Symposium,Fort Lauderdale, April 2002.

3. S. Basagni, C. Petrioli, "Multihop Scatternet Formation for Bluetooth Networks" IEEE VTC 2002, Birmingham, May 6-9, 2002.

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# Bluetooth on the market

| Company | Device | Cost |
|---|---|---|
| TDK, Toshiba, Anycom, Windport | Bluetooth PC Card | 159 – 179 Eur |
| Ericsson | Mobile Phone | 345 Eur |
| TDK | PDA | 215-229 Eur |