Context-aware Middleware for Multi-hop Multi-path Heterogeneous Connectivity in Social Sharing Scenarios

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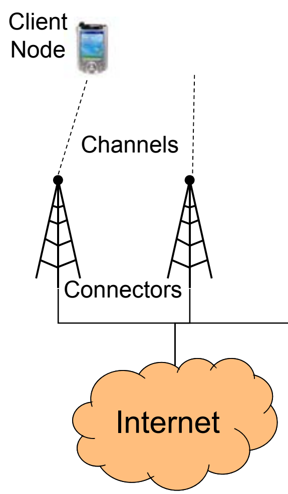
18.09.2009

Agenda

- Wireless scenario state-of-the-art analysis
  - **CAMPO** model and taxonomy
  - from traditional homogeneous to novel **heterogeneous** wireless scenarios
    - several communication technologies
    - infrastructure and peer points of access/services
- **Social sharing** of connectivity resources
  - dynamic management of **heterogeneous** connectivity resources
  - **sharing** of Internet connectivity and peer-to-peer services
  - pushing for node **cooperation**
- Multi-hop Multi-path Heterogeneous Connectivity (**MMHC**)
  - middleware for **context-aware dynamic reliable connections** to the Internet
  - context information: node mobility, path throughput, energy availability
  - MMHC vs. IEEE 802.11s
- Ongoing work
  - from Internet-based to **p2p-driven networking**
  - incentives to resources exploitation fairness in semi-cooperative environments
  - cluster-based mobility and smart environment management

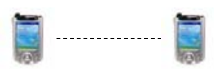
The Wireless Scenario

- **Client**: node **requiring** connectivity, e.g., user PDA
- **Connector**: node **providing** connectivity, e.g., UMTS Base Station (BS)
- **Channel**: active client-connector IP connection, e.g., IEEE 802.11 association and DHCP configuration
- **Handover procedure**
  - a client node **changes** current **connector** while moving
- **Evaluation process**
  - **context gathering**: which information is important?
  - **metric application**: which is the most suitable connector?



Single/Multi-hop Wireless Networking

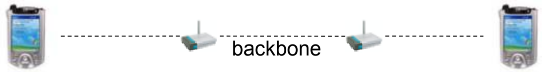
- Single-hop networking: **direct communication** among nodes
  - **ad-hoc**: point-to-point communication
    - Bluetooth Piconet or IEEE 802.11 IBSS
  - **infrastructure**: communication mediated by special purpose equipment
    - IEEE 802.11 AP or UMTS BS



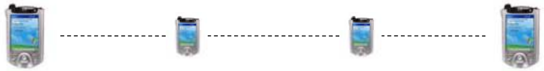
- Multi-hop networking: communication among distant nodes based on packet **routing performed by intermediate nodes**
  - different hypothesis on
    - availability of **infrastructure components**
    - **mobility degree** of communicating and intermediate nodes

WMN, MANET, Opportunistic Networking

- Wireless Mesh Network, **WMN**
  - intermediate nodes are mainly **infrastructure-based**, aiming at creating highly **reliable backbones**, e.g., IEEE 802.11s
  - communicating nodes move frequently, **intermediate** nodes are rather **static**



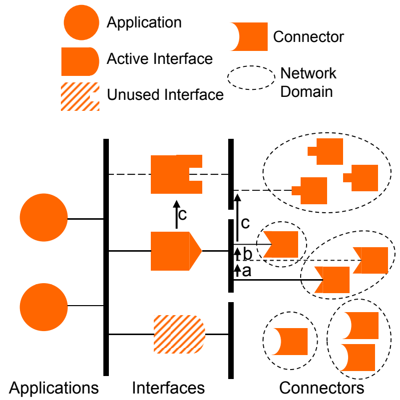
- Mobile Ad-hoc NETwork, **MANET**
  - intermediate nodes are based on **ad-hoc** connectivity: **best-effort** connectivity
  - both communicating and **intermediate nodes move frequently**, but there is enough time to create sufficiently reliable paths among nodes



- **Opportunistic Networking**
  - similar to MANET, but **without a path** among communicating nodes
  - intermediate nodes **opportunistically forward packets** whenever interact with other nodes "closer" to the destination: suitable in **unreliable environments**

CAMPO Model (1)

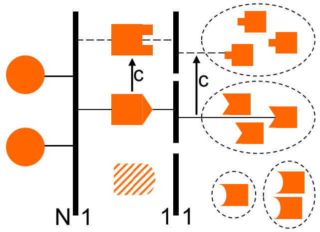
- Thorough **state-of-the-art survey**
- **Many specific** research **areas**, e.g., infrastructure-based and peer-to-peer
- Novel **model and taxonomy**:
  - proposals **grouping** based on differences and similarities
  - novel researchers field comprehension
- **CAMPO**: Context-aware Autonomic Management of Preferred network Opportunity
  - <u>most **suitable interface** and **connector** </u>based on user preferences, runtime environment, connectivity reliability
- A **common model** for
  - basic **term** definition
    - channel: {application, interface, connector}
    - intra/inter/vertical handover
  - two **selection mechanisms**
    - interface and connector selector



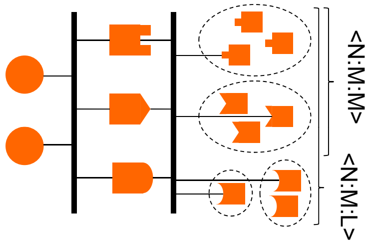
a) Intra-horizontal, b) Inter-horizontal and c) vertical handover

CAMPO Model (2): 4G and ABC

- **4G** (4th Generation)
  - one interface per time, selected without user intervention <N:1:1>
  - infrastructure-based connectors
  - dynamic **connection migration** among interfaces



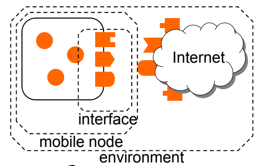
- **ABC** (Always Best Connected)
  - several interfaces simultaneously
  - infrastructure and **peer connectors**
  - only-one/multiple channels per interface <N:M:M> / <N:M:L>

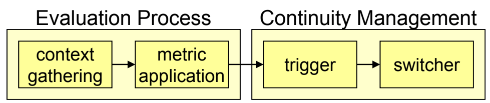


- **Social Sharing**
  - Internet connectivity + **peer-to-peer services**
  - user's behavior **active monitoring**
  - **reward**-based mechanisms

CAMPO Taxonomy (1)

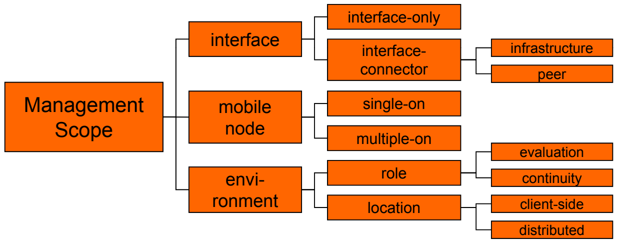
- Three **categories** to underline specific similarities and differences:
  - management scope
    - working environment capabilities
  - evaluation process
    - context gathering: which information are important?
    - metric application: which interface/connector is the most suitable one?
  - continuity management
    - trigger: when performing a handover?
    - switcher: how to update active channels?





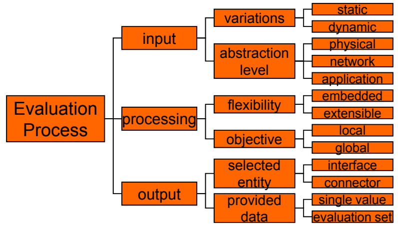
CAMPO Taxonomy (2)

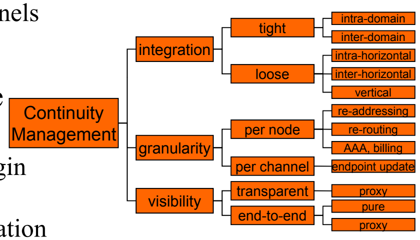
- Management scope:
  - interface: switch on/off, select a connector
  - mobile node: only one/multiple interfaces
  - environment: external components support



CAMPO Taxonomy (3)

- **Primary operations** of CAMPO systems
- Evaluation process
  - available **channels suitability**
    - input: context information
    - processing: how to exploit input
    - output: channel suitability, best channels
- Continuity management
  - **update active channels** at service provisioning time
    - integration: relationship between origin and destination connectors
    - granularity: every-/per-channel migration
    - visibility: external support





CAMPO Taxonomy (4)

CAMPO System	Deployment Scenario			Evaluation Process			Continuity Management		
	interface	mobile node	environment	input	processing	output	inte-gration	granu-larity	visibility
[19]	interface	mainly single-on	eval on client, cm on infra	static, phy	embedded, local	interface, single value	loose	per node	proxy
[52]	infrastructure	single-on	eval on infra	static, net	embedded, global	connector, single value	na	na	na
[20]	interface (infrastructure)	single-on	eval on client, cm on infra	primarily static, phy	embedded, local (global)	both, single value	tight	per node	transparent
[50]	infrastructure	single-on	eval on client	dynamic, phy	embedded, local	connector, single value	tight	per node	transparent

- A survey positioning about 80 work
  - many systems provide only **partial solutions**
  - deployment scenario: connector scope, **single-on**
  - evaluation process: **local** scope, function, connector
  - continuity management: **loosely**-coupled, per-node, proxy

Lessons Learned

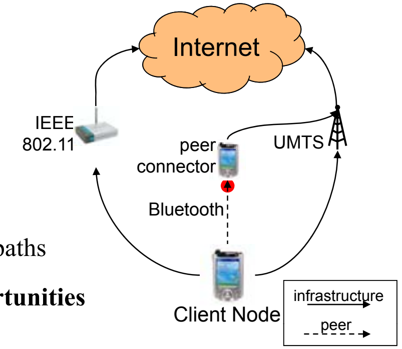
- **Context-aware** evaluation process
  - dynamic adaptation of the execution environment
  - trade-off between effectiveness and expressiveness
- **Hybrid** deployment scenarios
  - infrastructure and peer connectors
  - multi-hop multi-path heterogeneous connectivity
- **Decentralized** connectivity management
  - collaborating components distributed on different nodes, eventually even on the infrastructure side

Homogeneous Wireless Scenario

- Current scenario: **static**, **infrastructure**-based, **one-hop**
- **One** communication **interface** at a time
  - the client node does not change wireless interface
- **Horizontal handover**
  - infrastructure connectors only
  - origin and destination connectors based on the same wireless technology
- **Simple** evaluation metric
  - IEEE 802.11: metric based on Received Signal Strength Indication (**RSSI**) and Signal to Noise Ratio (SNR), usually embedded in interface firmware
- Already available **many** heterogeneous wireless **interfaces** on the **same** mobile **node**
  - IEEE 802.11, Bluetooth, GPRS/UMTS
  - bandwidth, power consumption, coverage range

Heterogeneous Wireless Scenario

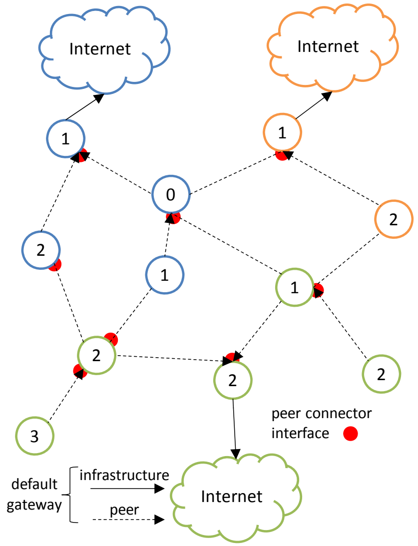
- **Heterogeneous interfaces**
  - the client node exploits **multiple wireless** interfaces, even simultaneously
- **Heterogeneous connectors**
  - can be **infrastructure** or **peer** nodes
  - single-/**multi-hop paths**
- **Connectivity management**
  - managing interfaces/connectors/channels/paths considering **several context data** to take advantage of the **many networking opportunities**



- **Heterogeneity** and **cooperation** increases client node capabilities:
  - heterogeneous connectors enable the **most suitable** form of connectivity
    - Bluetooth to limit power consumption, IEEE 802.11 to get larger bandwidth
  - peer connectors **extend connectivity** opportunities via multi-hop **paths**
    - UMTS link accessed via Bluetooth through a peer connector

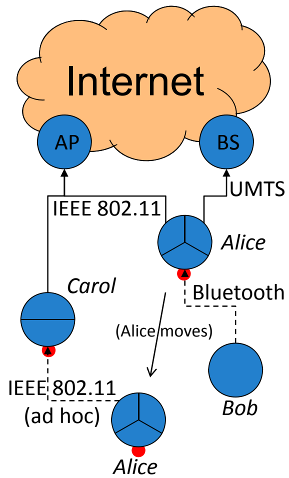
Social Sharing of Connectivity Resources (1)

- Novel scenario taking full advantage of the **many** context information and **networking opportunities**
  - peer-to-peer connectivity
  - simultaneous exploitation of multiple interfaces
  - average node mobility (between MANET and WMN)
- **Internet** sharing
  - Internet connectivity provisioning based on **dynamic context-aware routing** rules configuration
- **Peer-to-peer service** sharing
  - time/hop-bounded service discovery/invocation in **heterogeneous ad-hoc networks**
- **Quality of Service control**
  - **incentive-based** to push for actual connectivity/service sharing



Social Sharing of Connectivity Resources (2)

1) Alice's client **autonomously selects** the free-of-charge IEEE 802.11 connector
2) Alice **provides connectivity** via Bluetooth
3) Carol provides her lesson's notes via a **file sharing service**
4) Bob accesses Carol's notes via Alice
5) When Alice moves, she gets connectivity via Carol and then **re-establish active connections**



Social Scenario: Design Guidelines

- Trade-off between **static and dynamic** management
  - re-evaluation of connectivity opportunities to
    - modify available channels
    - reconfigure routing rules
  - **static** approaches achieve **sub-optimal solutions**
  - **dynamic** approaches impose non-negligible monitoring/managing **overhead**
- Trade-off between **local and global** management
  - monitoring scope greatly impact on required solution
    - **local knowledge**: easy to gather but with limited expressiveness
    - **global knowledge**: best resource exploitation but with networking overhead and delay
- Trade-off between **single- and multi-path granularity**
  - basic solution: every flow of **every client** sent to the same destination
    - aggregated routing rules
  - client-granularity: different flows of the **same client** sent to the same destination
    - per-client routing rules
  - flow-granularity: **each flow** is managed differently
    - per-request routing rules

MMHC: Multi-hop Multi-path Heterogeneous Connectivity

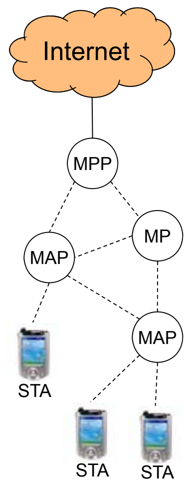
- Full exploitation of already available wireless interfaces
  - **multi-hop paths**, eventually based on heterogeneous single-hop links
  - **dynamic** connectivity evaluation and management
  - **connectivity provisioning** in a peer-to-peer fashion
  - **context-aware** evaluation metric
- **Efficient connectivity** support via proper trade-off among
  - static and dynamic management
    - time-consuming **single-hop** connections performed reactively (rather **static**)
    - efficient **routing rules** modifications performed proactively (**dynamic**)
  - local and regional management
    - **local** management to quickly provide **Internet connectivity**
    - **regional** management to incrementally **improve** connectivity capabilities
  - single- and multi-path granularity
    - **aggregated connectivity** to the Internet
    - differentiated access to peer to peer services

MMHC: Objectives

1) **Novel metric** considering a wide set of context information at different abstraction levels
   - traditional RSSI/SNR based evaluation processes are not enough
   - **evaluation metric** specifically designed for heterogeneous wireless scenarios
2) **Two-phase** procedure to separately consider path **establishment** and **enhancement**
   - **local-phase**: connectors suitable for **path** realization to maximize reliability and throughput
   - regional-phase: long-term connectivity based on additional context information, eventually slight modifications of the network topology
3) Static and dynamic management
   - **reactive** approach for single-hop connectivity
   - proactive approach for **multi-hop** path reconfiguration

IEEE 802.11s for Extended Service Set mesh networking

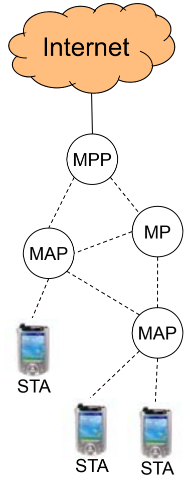
- Multi-hop connectivity at lower OSI layers, by extending IEEE 802.11
  - **efficiency**: no en/decapsulation of data into/from higher layer protocols
  - **availability**: compatibility with the many already available IEEE 802.11a/b/g interfaces
- Node roles
  - STA: mobile **client** STAtion only getting connectivity
  - MAP: Mash Access Point **providing connectivity** to STAs
  - MP: Mesh Point performing as **intermediate node** (not providing connectivity to STA)
  - MPP: Mesh Portal interconnecting the mesh network and the **Internet**
- Path establishment
  - metric: **airtime cost** reflecting the amount of **channel resources consumed** by transmitting a frame over a particular link
  - path selection: hybrid reactive/proactive



MMHC vs. IEEE 802.11s

- Both IEEE 802.11s and MMHC support multi-hop wireless connectivity, but with relevant differences
- **Roles**
  - IEEE 802.11s: STA, MP, MAP, MPP
  - MMHC: clients, (peer) connectors
- **Layer**
  - IEEE 802.11s: MAC protocol
  - MMHC: interconnection of **IP networks**
- **Technology**
  - IEEE 802.11s: only standard-compliant interfaces
  - MMHC: interconnection of **heterogeneous networks**
- Evaluation **metric**
  - IEEE 802.11s: low-level radio-aware link metric
  - MMHC: meaningful **context** information

- IEEE 802.11s and MMHC are **complementary**, not competitors



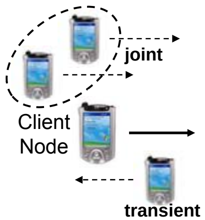
Context Awareness

- Provide **highly reliable/durable paths** (crucial issue in mobile wireless networks) with **sufficient quality** (to maximize user satisfaction)
- Path **reliability**
  - peer connectors are less reliable, since may abruptly **move away**
  - monitor client node and peer **mobility** to provide **reliability**
- Path **quality**
  - quality mainly depends on wireless **technology**, number of **active clients**, and number of **hops** to the Internet
  - coarse-grained estimation of actual **throughput**
- Path **durability**
  - interrupt the connectivity to limit **power consumption**
  - **residual battery** level to ensure path **long-term durability**

Path Reliability (1)

- **Transient** connector
  - e.g., a mobile node in the same sidewalk but with opposite direction
  - **not suitable** for connectivity since has a high probability of **becoming unavailable**
- **Joint** connector
  - e.g., PDA connector in the same train wagon
  - **greater durability** → **suitable** for connectivity

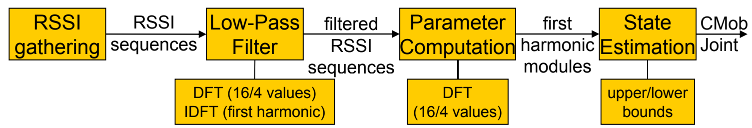
- Client-connector **mutual distance** inferred by monitoring connector **RSSI variability**
  - **CMob** to evaluate **client** node mobility degree [0,1]
  - **Joint** to evaluate peer **connector** relative mobility degree [0,1]



Connector type	RSSI variability	Mobility state
fixed	almost constant	still client node
	greatly variable	moving client node
mobile	almost constant	joint connector
	greatly variable	transient connector

Path Reliability (2)

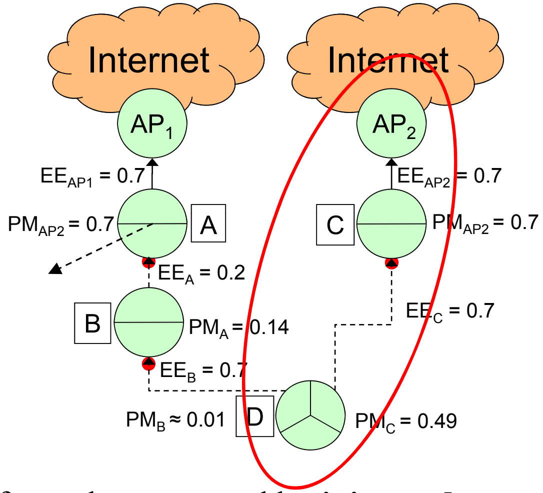
- **Discrete Fourier Transform (DFT)** applied twice to
  - low pass **filter RSSI fluctuations** due to signal noise
  - estimate **CMob** (fixed infrastructure connectors) and **Joint** (peer connectors)



- Single-hop: **EstimatedEndurance**
  - (1-CMob) • CoverageRange (for APs/BSs)
  - Joint • CoverageRange (for mobile peers)
- Multi-hop: **PathMobility** at k[th] hop
  - $EstimatedEndurance_k$ (single-hop, i.e., k=1)
  - $EstimatedEndurance_k$ • $PathMobility_{k-1}$ (multi-hop, i.e., k>1)

Path Reliability (3)

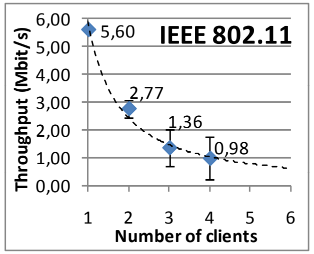
- Node B and C are still
  → high EE
- Node A is in motion
  → low EE
- Node D **automatically** selects the path on the right
  - nodes B and C have same EE but **different PM**
  - node C provides much **higher reliability** (PM_B=0.49 vs. PM_A=0.14)

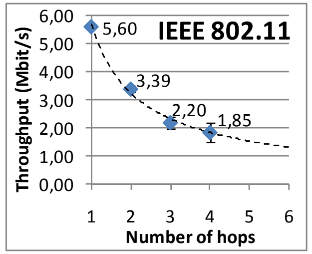


- Lessons learned: push for paths composed by **joint nodes**

Path Quality (1)

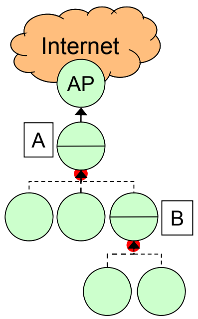
- Coarse-grained estimation of **multi-hop paths throughput**
  - adopted **wireless technology**: e.g., Bluetooth represents a bottleneck
  - number of **active clients**: fair bandwidth sharing
  - number of **hops** to the Internet: 20-30% per-hop degradation





- **Heterogeneous wireless interfaces** provided by different manufactures, e.g., IEEE 802.11 Orinoco Gold, Buffalo and PRO/Wireless interfaces
  - heterogeneous interfaces better mimics actual wireless environments
  - greater performance with homogeneous hardware

Path Quality (2)



- EstimatedThroughput (ET):
  - NominalBandwidth (NB) (for APs/BSs)
  - (1 – HopDegr) • MaxThr / #clients (for mobile peers)
    - where MaxThr=min{previous hop ET, current hop NB}
  - $ET_{AP} = NB_{AP}$ = 4 Mbps
  - ET_A = (1-0.2) • 4 Mbps / 3 clients = 1.07 Mbps
  - ET_B = (1-0.2) • 1.07 Mbps / 2 clients = 0.428 Mbps
- Lessons learned: push for **short paths** with **few clients**, particularly when exploiting Bluetooth

Path Durability (1)

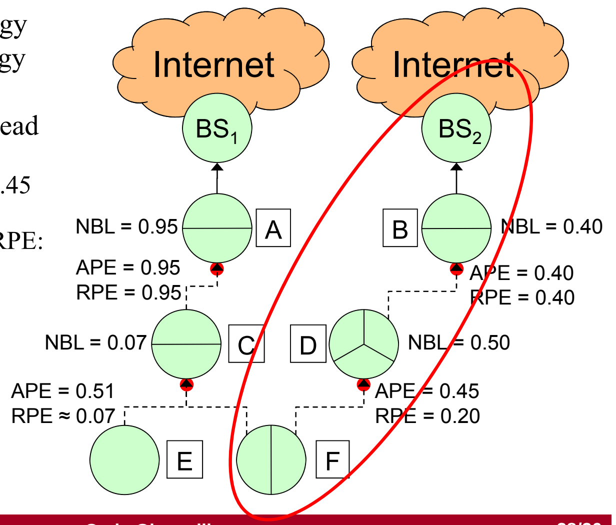
- Expected **long-term path durability** due to **energy consumption**
  - avoid paths composed by mobile peers with **low battery levels**
    - probably unavailable in a short time
  - **fairly exploit energy** of mobile peers not overloading only one path
    - traversing traffic increase power consumption
- ResidualPathEnergy at k^{th} hop
  - $NodeBatteryLevel_k$ (single-hop, i.e., k=1)
  - $NodeBatteryLevel_k$ • $ResidualPathEnergy_{k-1}$ (multi-hop, i.e., k>1)
- AveragePathEnergy at k^{th} hop
  - $NodeBatteryLevel_k$ (single-hop, i.e., k=1)
  - $\frac{(AveragePathEnergy_{k-1})\cdot(k-1)+NodeBatteryLevel_k}{k}$ (multi-hop, i.e., k>1)

Path Durability (2)

- NBL: NodeBatteryLevel
- RPE: ResidualPathEnergy
- APE: AveragePathEnergy

- **F selects BS2-B-D** instead of BS1-A-C
  - slightly lower APE: 0.45 instead of 0.51
  - but sufficiently great RPE: 0.20 instead of 0.07

- Lessons learned: push for battery level **fair exploitation**



MMHC Local Phase

- Main goal: **quickly achieve connectivity** to the Internet
  - locally gathers RSSI and estimates CMob/Joint
  - performs **single-hop reliable connections** based on EstimatedEndurance (completely distributed evaluation)
  - select the most suitable path based on PathMobility and EstimatedThroughput (distribution of few crucial context information)

- Local phase **path selection metric**: select the path with best trade-off among **PathMobility** and **EstimatedThroughput**:
  - avoid highly unreliable paths
  - maximize throughput
- **Reactively** activated at path disruption

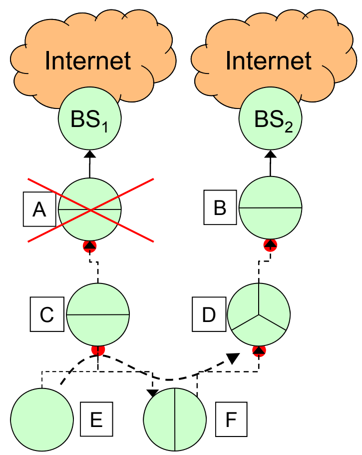
- **Greater priority to connection reliability** than quality

MMHC Regional Phase

- Main goal: ensure **long-term availability** enhancing connectivity capabilities
  - **periodically** interact with nearby node to **collect** PathMobility, EstimatedThroughput, AveragePathEnergy and ResidualPathEnergy
  - trigger **path modification** whenever a link is broken (reactive), ResidualPathEnergy lowers below 0.1 (proactive), or PathMobility lowers below 0.3 (proactive)
  - **select the path** with best trade-off among EstimatedThroughput and AverageBatteryEnergy
    - avoid nodes with low battery level
    - fairly exploit available paths
    - achieve high connectivity quality

- Maximize user perceived quality of service
  - available paths **periodic monitoring** and **proactive reconfiguration**
  - enhance connectivity opportunities via the **role-switch procedure**

Role-switch Procedure



- A client can work as **bridge** among different networks
  - the **peer connector** contribute providing the **physical network**, e.g., performing as Bluetooth master
  - a **client** starts **forwarding data** via one of its available paths: it acts as a gateway
- Note: role-switch aim at providing only **Internet connectivity**

- F has two paths to the Internet
- When A fails **C exploits F as gateway**
- Both C and E keep connectivity to the Internet via F

Ongoing Work

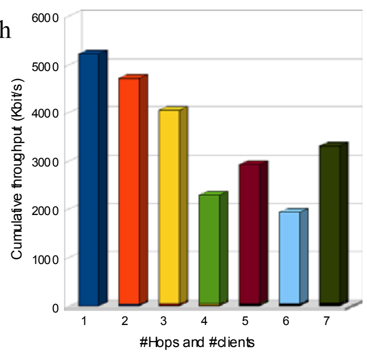
- Current MMHC prototype is mainly focused on **Internet connectivity**
  - main goal is to provide multi-hop Internet access to nodes
  - peer-to-peer communication limited to subnets
- Extending Internet connectivity provisioning via **peer-to-peer** networking
  - incremental knowledge of the (whole) wireless environment
  - **local (vs. Internet) service** provisioning/discovery/invocation
- Pushing for service/**connectivity provisioning**
  - supporting trust and fairness in semi-cooperative environments

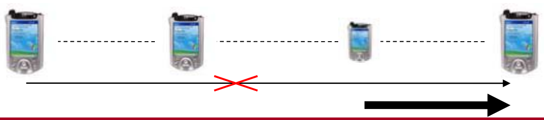
Peer-to-peer Information Delivery

- Supporting context **information spreading** among **NAT-separated** but interconnected networks
  - not only top-down but also **bottom-up and sibling** information delivery
- Information delivery with **no global knowledge** of network topology
  - multiple single-hop information dissemination among **neighbor nodes**
  - **time/hop bounded** information delivery
- **Service discovery/provisioning** as a special case of context distribution
  - context-aware service discovery/selection
  - automatic service rebinding

Connectivity Fairness in Multi-hop Wireless Networks

- Connectivity **starvation** in multi-hop **multi-client** paths
  - closest node achieves almost all the bandwidth
- **Decentralized fairness management**
  - traffic monitor to **perceive starvation**
  - traffic control to
    - maximize local traffic
    - avoid traffic starvation
- **Incentives** for connectivity sharing based on low/high level context information
  - traversing vs. generated packets
  - number of invoked/offered services
  - number of connected nodes





Conclusions & Ongoing Work

- MMHC supports **multi-hop multi-path** connectivity exploiting off-the-shelf **heterogeneous equipment**
  - IEEE 802.11, Bluetooth, Ethernet
- MMHC proposes **innovative context data** suitable for heterogeneous wireless scenarios
  - node mobility, path throughput, energy availability
- MMHC main goal is to provide **reliable connections** in wireless mobile environments
  - throughput as secondary objective
- Ongoing work
  - **Social Sharing:** from Internet-based to peer-to-peer connectivity
  - **security** issues: peer mutual authentication, user incentives, dynamic level of trust management
  - spontaneous **smart environments** based on dynamic clustering

Any question?

- Prototype code and implementation insights:
  - http://lia.deis.unibo.it/research/**MAC**/
  - http://lia.deis.unibo.it/research/**MACHINE**/
  - http://lia.deis.unibo.it/research/**MMHC**/
  - http://lia.deis.unibo.it/Staff/**CarloGiannelli**/