Research Areas in
Mobile Ad-Hoc Networks

LIM lab/JAIST meeting, Oct.03 2012

By

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A gateway to outreach the world while studying in Vietnam

Contents

- Routing in MANETs, and Internetworking MANETs with Internet
- Mobility Management in All-IP Mobile Networks
- Collaboration MANETs/WSNs
  - In Continuity with Presentation at 09.30-10.30
- Wireless Ad-Hoc Router
  - Presented at 14.00-14.30

Routing in MANETs, and Internetworking MANETs with Internet

Formerly funded by EuroNGI project: “Convergence of Multi-Service Networks towards Next Generation of Internet”, Europe FP6 ICT Network of Excellence-NoE [10/2004-10/2006], and

By EuroFGI project: “Convergence of Multi-Service Networks towards Future Generation of Internet”, Europe FP6 ICT Network of Excellence-NoE [11/2006-05/2008]

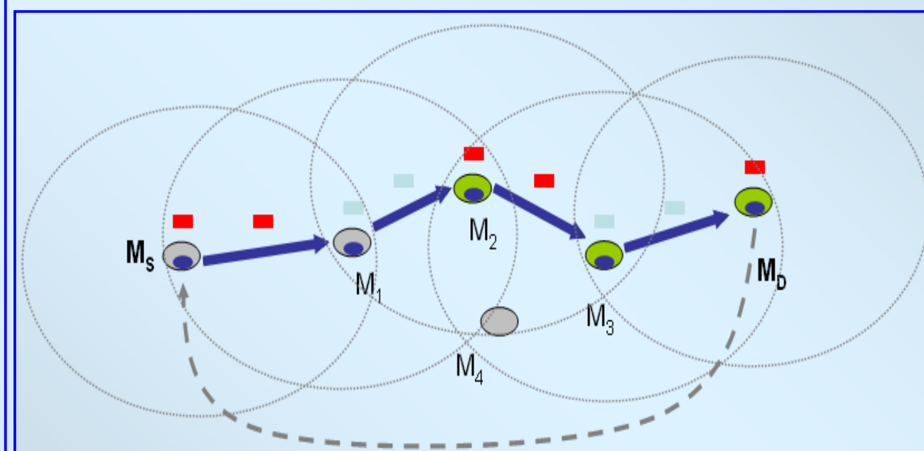
Motivations Introduction

- Mobile Ad Hoc Networks (MANETs)
  - Highly dynamic and Mobile
  - Infrastructureless, Unpredictable
  - Multi-Hop, Peer-to-Peer
- MANETs Features
  - Increased mobility and flexibility
  - Fast and economical deployment (reduces fixed infrastructure costs)
  - Increased spectrum reuse
  - Auto-configuration
  - Ability to inter-network through multi-hopping without using fixed network infrastructure
  - Increased robustness
- MANETs Applications
  - DoD (battlefields, communications)
  - Commercial (disasters, explorer, festivals,...)
- Technical Challenges of MANETs
    - Mobility
    - Scalability
    - Bandwidth constraint
    - RF Connectivity
    - Energy constraint
    - Routing fairness
    - Cluster cooperation
    - Distributed information processing
  - **Internetworking**

Cross-Layer?

Solutions mostly for Standalone MANET!

Source: (Chris Ellis, Dec.2004)
http://usipv6.unixprogram.com/usipv6_reston_2004/wed/Ellis.pdf



Source: (Seoung-Bum Lee, 2000)
http://comet.columbia.edu/insignia/slides/net2000.ppt

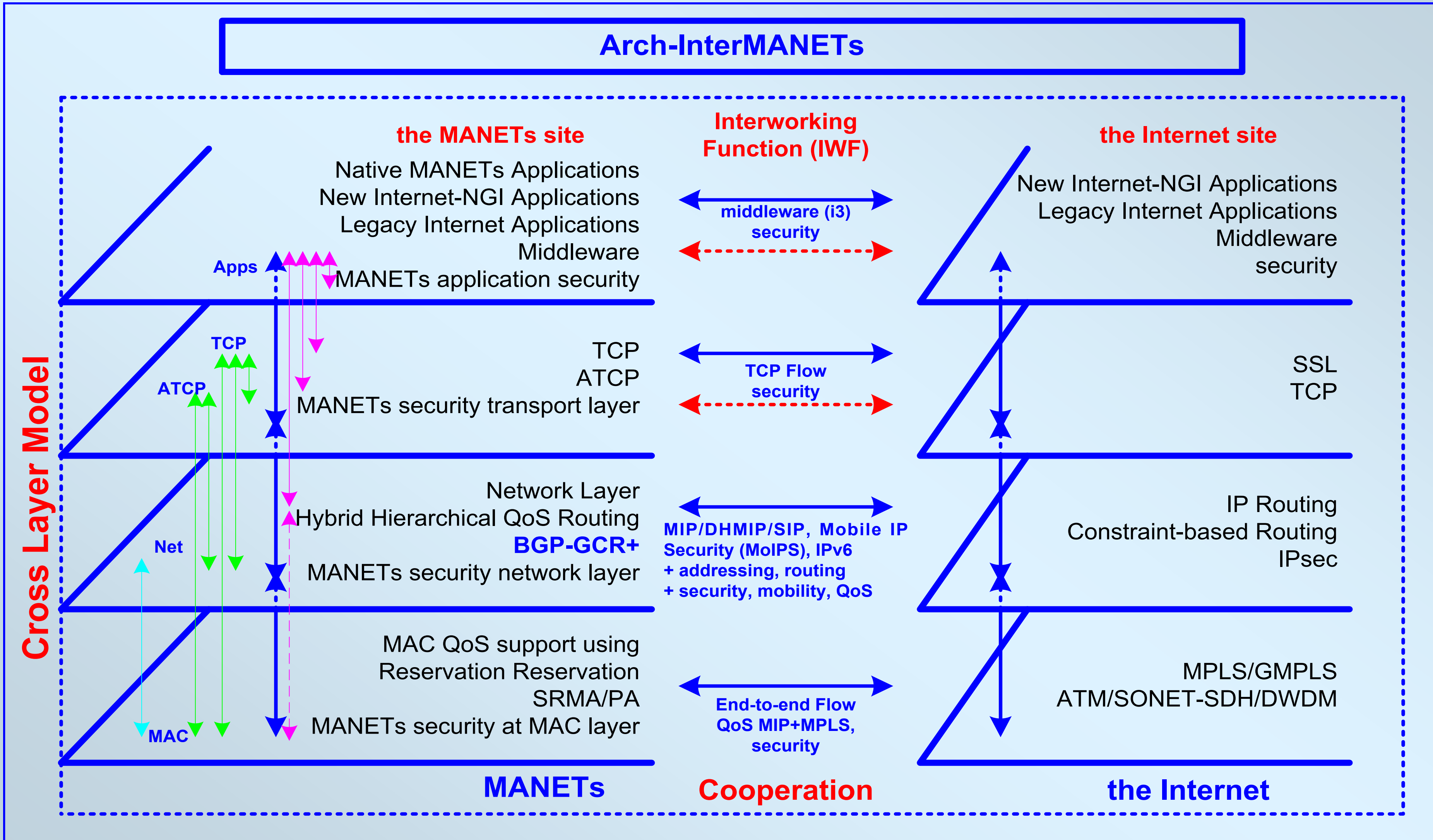
Motivations Objective

- Bring Advantages of MANETs to Internet (ISPs, Users)
    - Fast deployment network at cheap cost
    - Instant applications where infrastructureless network is needed, e.g. exploration, battle fields, disaster,…
    - Load balancing for congested networks
    - Extended coverage area of infrastructure wireless networks (1-hop) to multi-hop and/or "Empty Area"
  - Provide Internet access to MANET Users
  - Integration of MANETs and Internet to create a global network ↔ MANET and Internet Users Transparency
- Bring Advantages of MANETs to Sensor Networks
  - Fast deployment MANET overlaying over WSAN for processing in the event areas **[REACTION to EVENTS]**
- Working Standardization (Internet Drafts, RFCs)

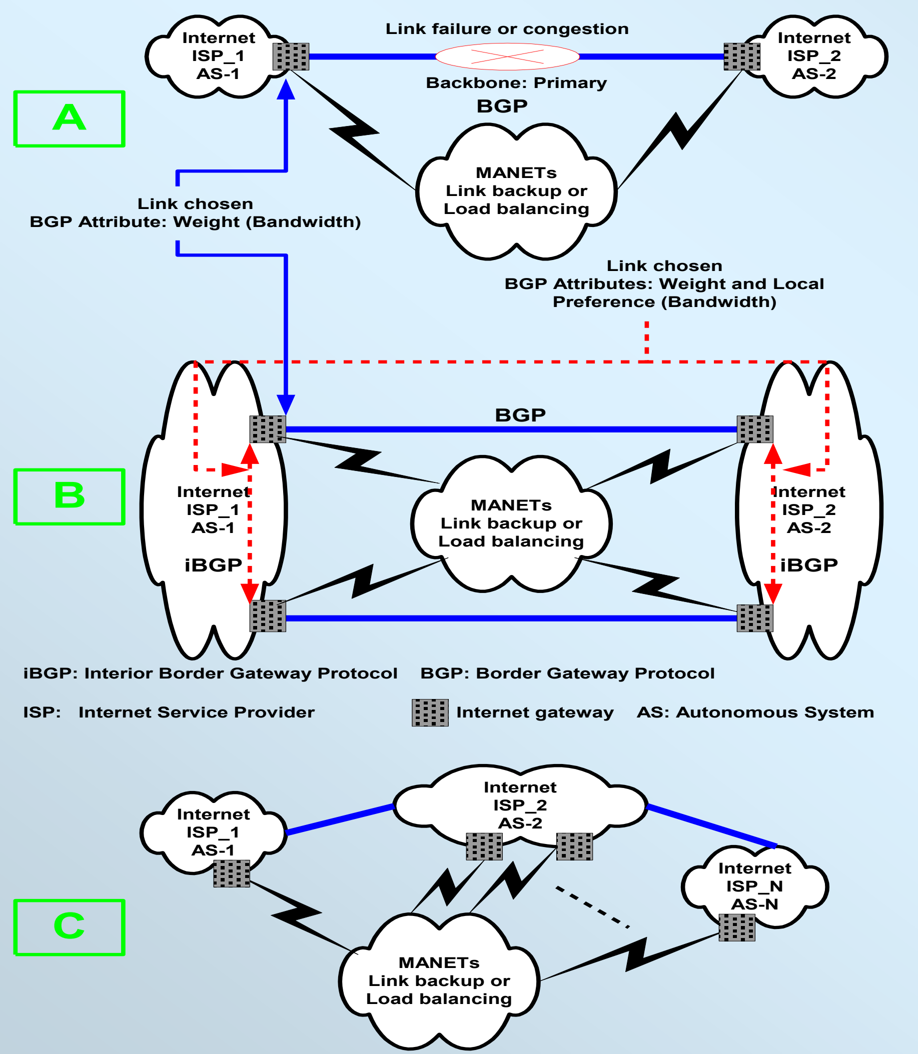
Motivations Scope

- Mainly working at the Network Layer (L3)
- Cross-Layer Relation (L3/L2) for Increasing Performance and Reducing Overhead/Packet Drops
- Performance Evaluation via Simulation in ns-2, testbed
- Point to Consider in Internetworking:
  - Addressing [MANET ↔ Internet] & Routing [Both]
  - Mobility Management [MANET ↔ Internet]
  - MAC Layer (L2) Cross-Layer Relation [MANET ↔ Internet]
  - Scalability [Both]
  - Energy-Efficiency [MANET↔WSAN]
- Point not to Consider in Internetworking:
  - Quality of Service Support
  - Security

Internetworking MANETs with the Internet



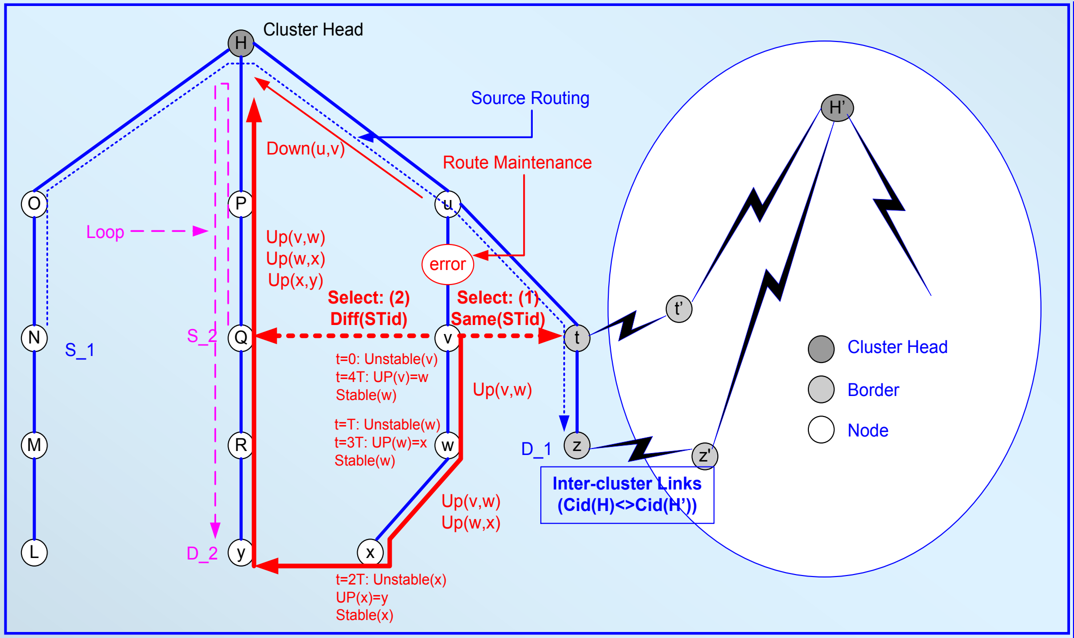
MANETs as Transit Networks for the Internet



Scenarios of MANETs as Transit Networks for the Internet: (A) One bacbone link between two AS systems, (B) Multiple backbone links between two AS systems, (C) Multiple AS systems are connected together

- Objectives
  - Routing in Large-Scale MANETs
  - MANETs as Backup, Load-Balancing Transit Networks for the Internet
- Problems stated
  - MANETs address stateless autoconfiguration
  - Hybrid ad-hoc routing
  - Scalability (clustering, hierarchy)
  - Towards standards
    - IPv6-based mechanism (IPv6 IETF charter)
    - MANETs IETF charter (Internet drafts, rfcs)
  - Internetworking: Type IV
    - Internet gateways connections (Inter-Autonomous Systems) via MANETs
    - Routing THROUGH MANETs via destination AS-number based
- Areas of Applications
  - Disasters (Links failures)
  - Link backup
  - Load-balancing

Routing Component of BGP-GCR+

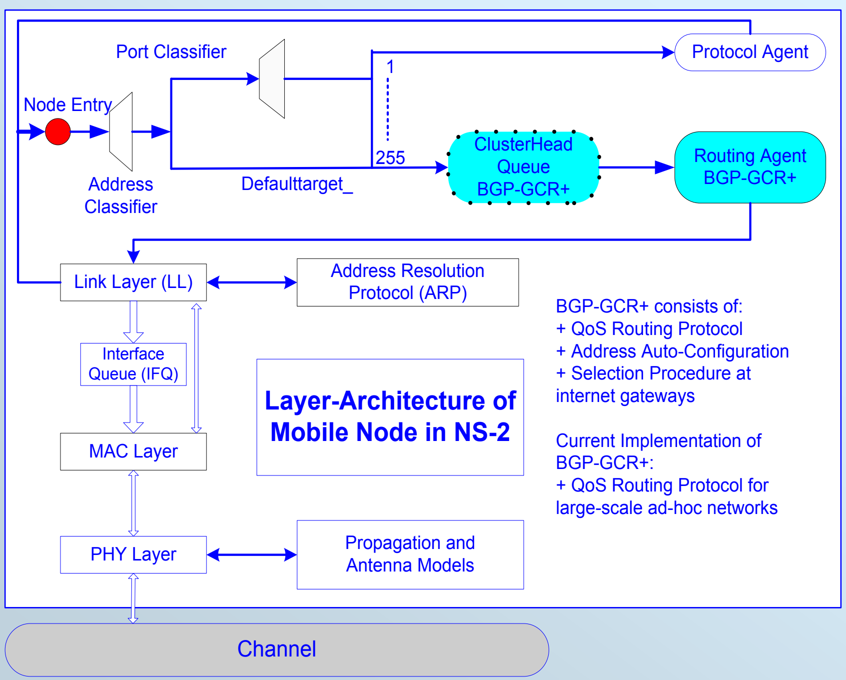


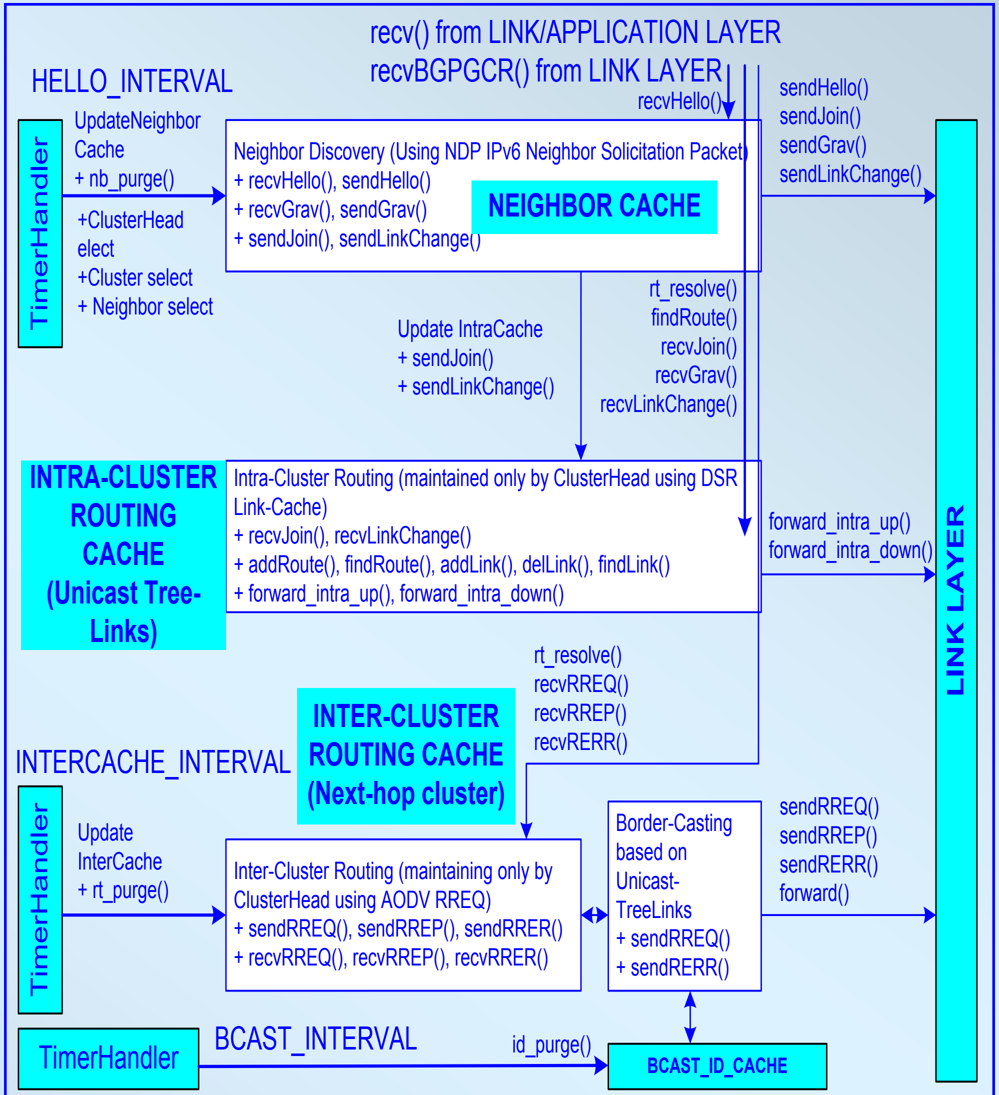
A summary of the characteristics of GCR	
Items	**Characteristics**
Clustering	Two-level
Cluster head election degree	Local (R=1) maximum degree
Cluster maintenance	One-node fault-tolerant Anti-fluctuations based on Gravitational clustering and node stability
Broadcast range	R_{max}
Overlapped area	No
Broadcast reduced	Unicast Tree
QoS support	Yes
Address assignment	Assumption assigned (any methods)
Area of application	Large-scale, dense MANETs
Space complexity of cluster head	O(n*AvgDeg(n)+$N_{cluster}$*AvgDeg(n)+AvgDeg(n))
Time complexity of cluster head	O(**f**(n*AvgDeg(n)+$N_{cluster}$*AvgDeg(n)+AvgDeg(n)))
Space complexity of others	O(AvgDeg(n))
Time complexity of others	O(**f**(AvgDeg(n)))

- Features of GCR
  - Hierarchy (two-level)
  - Hybrid
    - Intra-cluster (centralized, leader-based, link-state)
    - Inter-cluster (on-demand AODV-based)
  - Cluster construction
    - Local maximum degree
    - Broadcast range (R_{max}), Non-overlapped
  - Cluster maintenance
    - One-node fault-tolerant (auto-repairable)
  - Area of application: large-scale, dense MANETs
- Limitations of GCR, Extension for **BGP-GCR+**
  - MANETs nodes are assumed to be assigned Unique IDs and Unique CIDs
  - MANETs nodes data structures, packet formats, route cache are not fully specified
  - Neighbor (cluster) selection criteria for nodes switching on

Implementation of BGP-GCR+ in ns-2

- BGP-GCR+ consists of three components
- Currently, Routing component of BGP-GCR+ is implemented in ns-2
  - Cluster Formation and Maintenance
  - Intra-Cluster/Inter-Cluster Routing
  - Data Structures
    - Neighbor Cache
    - Intra-Cluster/Inter-Cluster Caches
    - Interface/BGP-GCR+ Queue and Policy

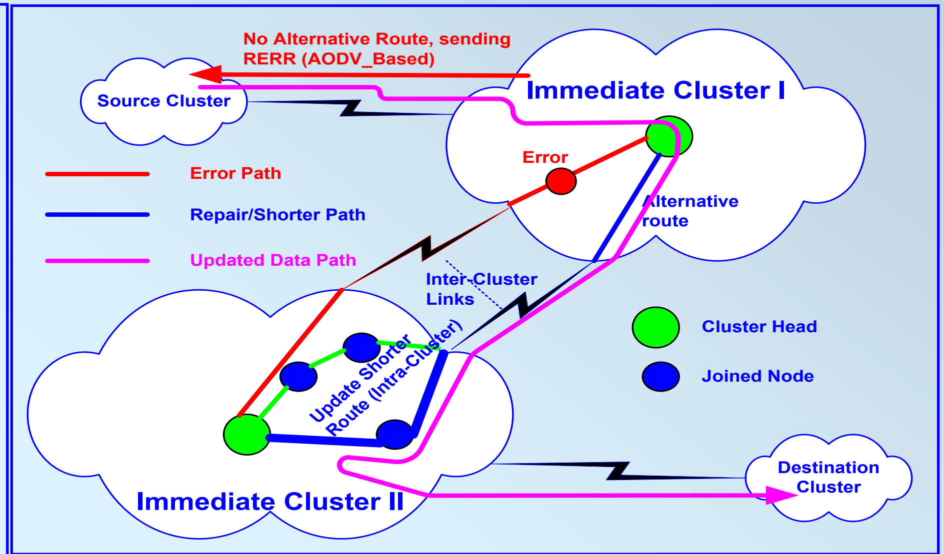


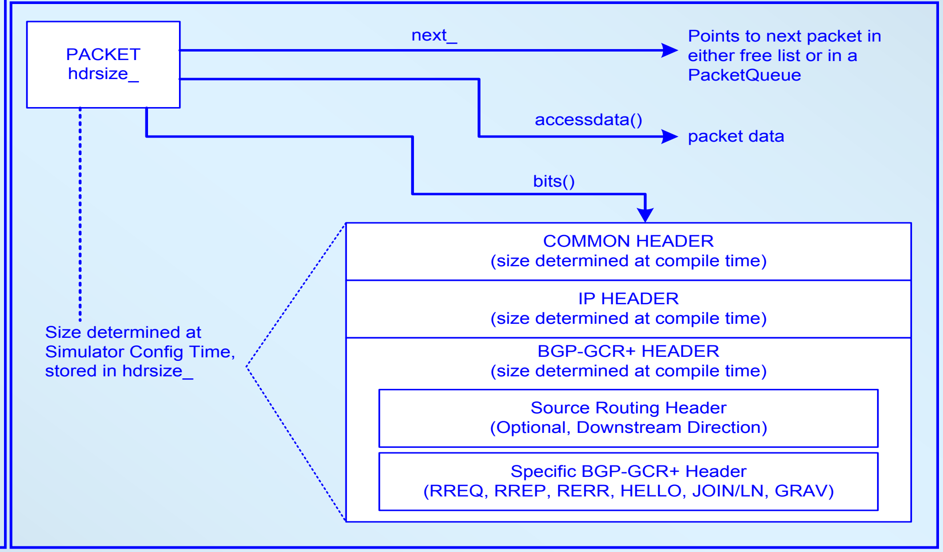


BGP-GCR+ Packet Flow

Implementation of BGP-GCR+ in ns-2

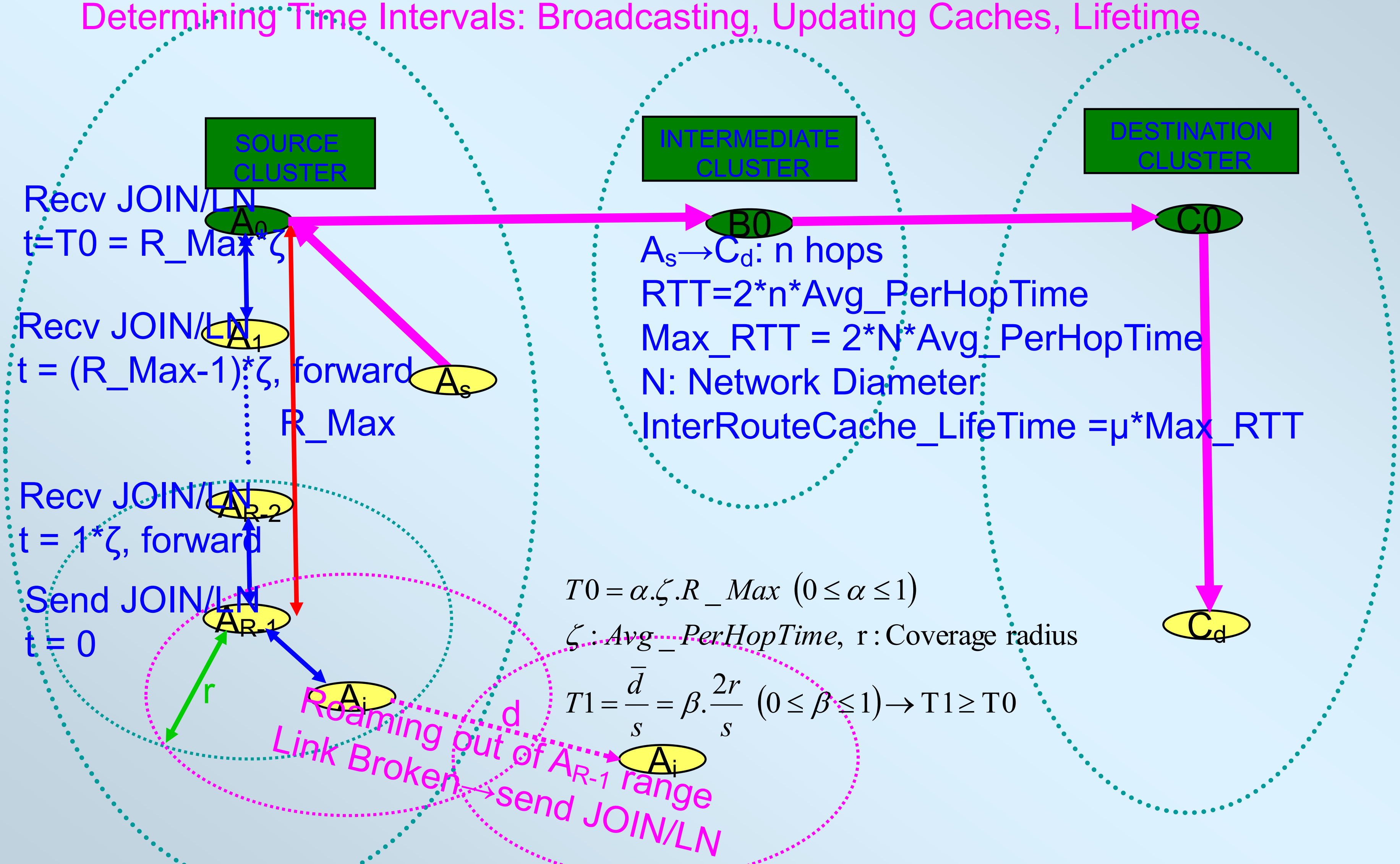
- Cluster Maintenance
  - Based on one-node fault-tolerant characteristics of Cluster Formation
  - Intra-Cluster Maintenance based on Link UP/DOWN sent to Cluster Head via Link-Change Packets from detecting nodes in its cluster
  - Inter-Cluster Maintenance based on AODV Route Maintenance (RERR sent to source the by detecting node)
- Neighbor Cache (Extension of AODV Neighbor Cache)
  - Double-Linked List, Timeout for each Entry, Periodically purged
  - Periodically send Hello packets to inform its existence to neighbors
- Interface Queue and Policy (Already Implemented in ns-2)
  - Queue/DropTail/PriQueue
- BGP-GCR+ Queue and Policy (Extension of AODV Data Queue)
  - Queue/DropTail
- Packet Headers and Formats
  - IPv6 Internet Drafts and RFCs (Data types is not exactly followed)
  - ns-2 Packet Headers (Common, IP)
  - AODV Packet Headers (RREQ, RREP, RERR)
  - DSR Packet Headers (Source Routing Header)
  - BGP-GCR+ (Hello, Join/Link-Change, Grav)





BGP-GCR+ over 802.11 DCF

Determining Time Intervals: Broadcasting, Updating Caches, Lifetime



$A_s \rightarrow C_d$: n hops

RTT=2*n*Avg_PerHopTime

Max_RTT = 2*N*Avg_PerHopTime

N: Network Diameter

InterRouteCache_LifeTime =μ*Max_RTT

$$T0 = \alpha.\zeta.R\_Max \ (0 \le \alpha \le 1)$$

ζ : $Avg\_PerHopTime$, r : Coverage radius

$$T1 = \frac{\bar{d}}{s} = \beta.\frac{2r}{s} \ (0 \le \beta \le 1) \rightarrow \mathrm{T1} \ge \mathrm{T0}$$

BGP-GCR+ over 802.11 DCF

Determining Time Intervals: Broadcasting, Updating Caches, Lifetime

$$T0 = \alpha * I_{N-Update-Fixed} * R\_Max * Avg\_PerHopTime \quad (\alpha \le 1, \text{R\_Max : cluster radius}) \qquad (1)$$

$$\text{T1} = \left(\frac{a.r}{Max\{speed\}} \right) (r : \text{node coverage radius}, 0 \le a \le 2, \text{Average} : \bar{a} = 1) \qquad (2)$$

$$T0 \le T1 \Leftrightarrow I_{N-Update-Fixed} \le \left(\frac{a.r}{Max\{speed\}} \right) . \frac{1}{R\_Max * Avg\_PerHopTime} \qquad (3)$$

$$\rightarrow I_{N-Update} = \left[(1-\beta_1) . I_{N-Update-Fixed} + 2.\beta_1 . I_{N-Update-Fixed} . Random :: uniform() \right] (\beta_1 = 0.90) \qquad (4)$$

$$\rightarrow I_{H-Broadcast} = \left[(1-\beta_2) . I_{N-Update-Fixed} + 2.\beta_2 . I_{N-Update-Fixed} . Random :: uniform() \right] (\beta_2 = 0.75) \qquad (5)$$

$$\rightarrow I_{N-Lifetime} = \left[1.5 * ALLOWED\_HELLO\_LOSS * I_{N-Update-Fixed} \right] \qquad (6)$$

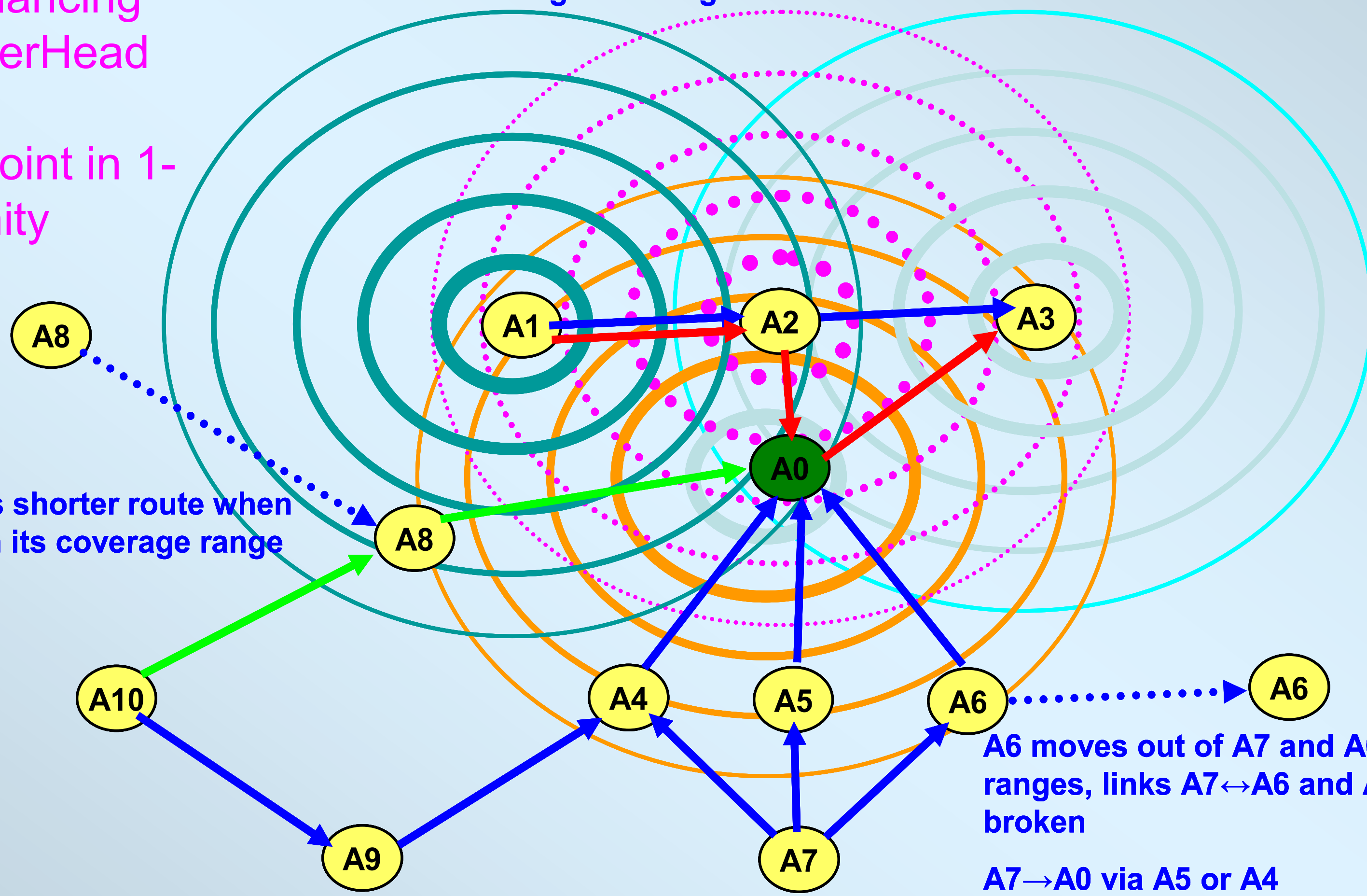
$$I_{R-Lifetime} = \mu_1 * Max\_RTT = \mu_1 * 2 * N * Avg\_PerHopTime \quad (\text{N : Network Diameter}) \qquad (7)$$

$$I_{R\_Update} = \mu_2 * Max\_RTT \quad (\mu_1 \ge 1, 1 \ge \mu_2 \ge 0.5) \qquad (8)$$

BGP-GCR+ over 802.11 DCF

Load-Balancing via ClusterHead and/or BranchPoint in 1-hop vicinity

A1→A3 via A2 using A2's NeighborCache instead of A1→A2 →A0 →A3



A10 updates shorter route when A8 moves in its coverage range

Multiple routes for Load-Balancing or Backup for A7

A6 moves out of A7 and A0 coverage ranges, links A7↔A6 and A6 ↔ A0 are broken

A7→A0 via A5 or A4

Link A5 ↔ A0 is congested

A7→A0 via A4

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Formerly funded EuroFGI project: “Convergence of Multi-Service Networks towards Future Generation of Internet”, Europe FP6 ICT Network of Excellence-NoE [11/2006-05/2008]

Mobility Management in All-IP Mobile Networks

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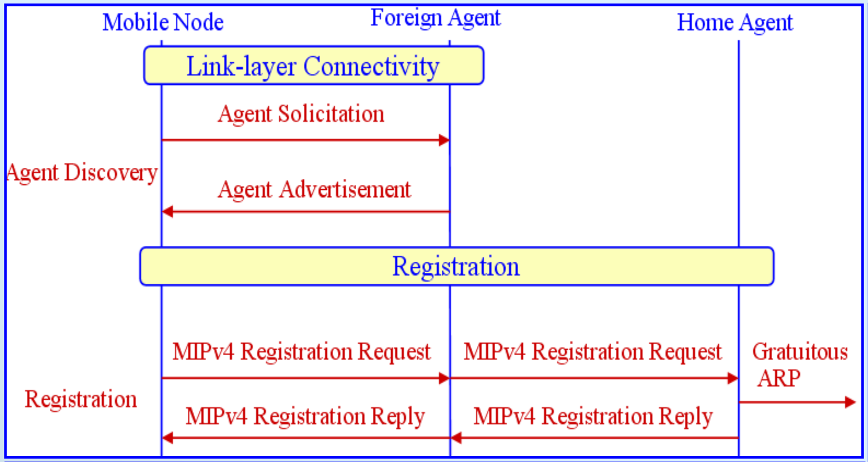
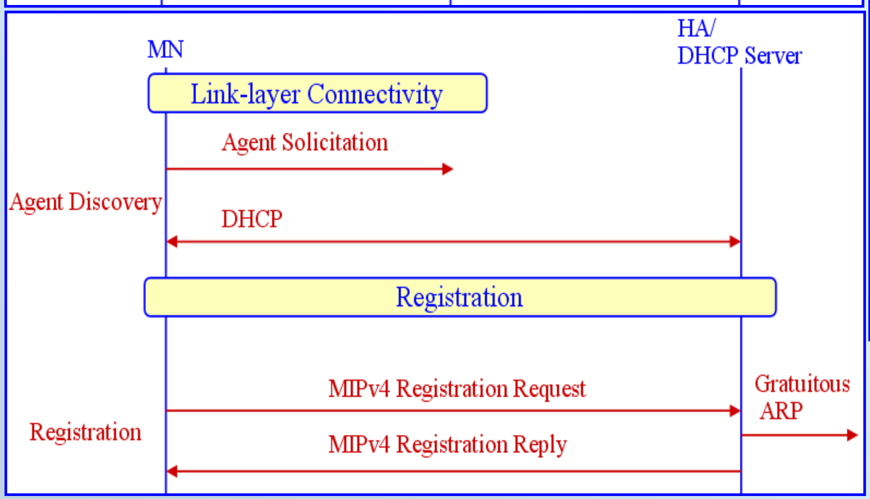
Contents

- A Review on existing mechanisms in Internet Mobility Management
  - IP Mobility Management
  - IP Mobility Management over WLAN (1-Hop)
  - IP Mobility Management over MANET (Multi-Hop)
- Needing functions on Internet connectivity for MANETs
- Discovering problems on Internet gateway forwarding strategies for MANETs & Solutions
- A new Internet gateway selection metric
  - Shortest Euclidean distance
  - Load-balancing for traffic in/out the Internet from/to MANET
  - Load-balancing for Internal MANET traffic

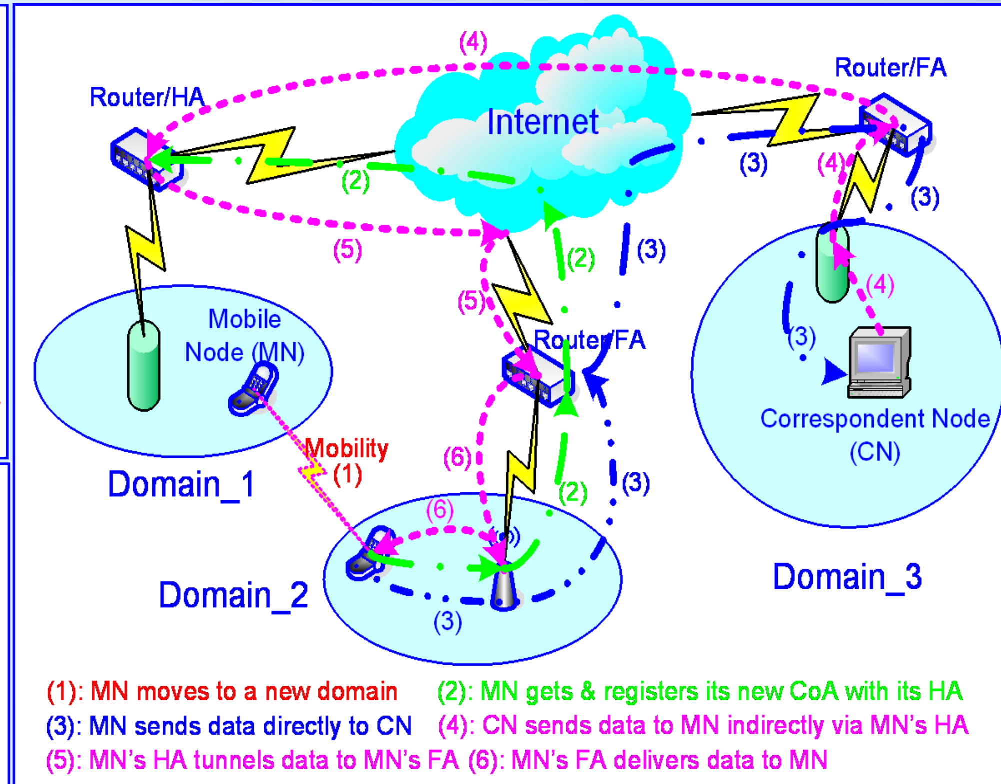
Review IP Mobility Management [MIPv4] (1/5)

Foreign Agent Care-of Address

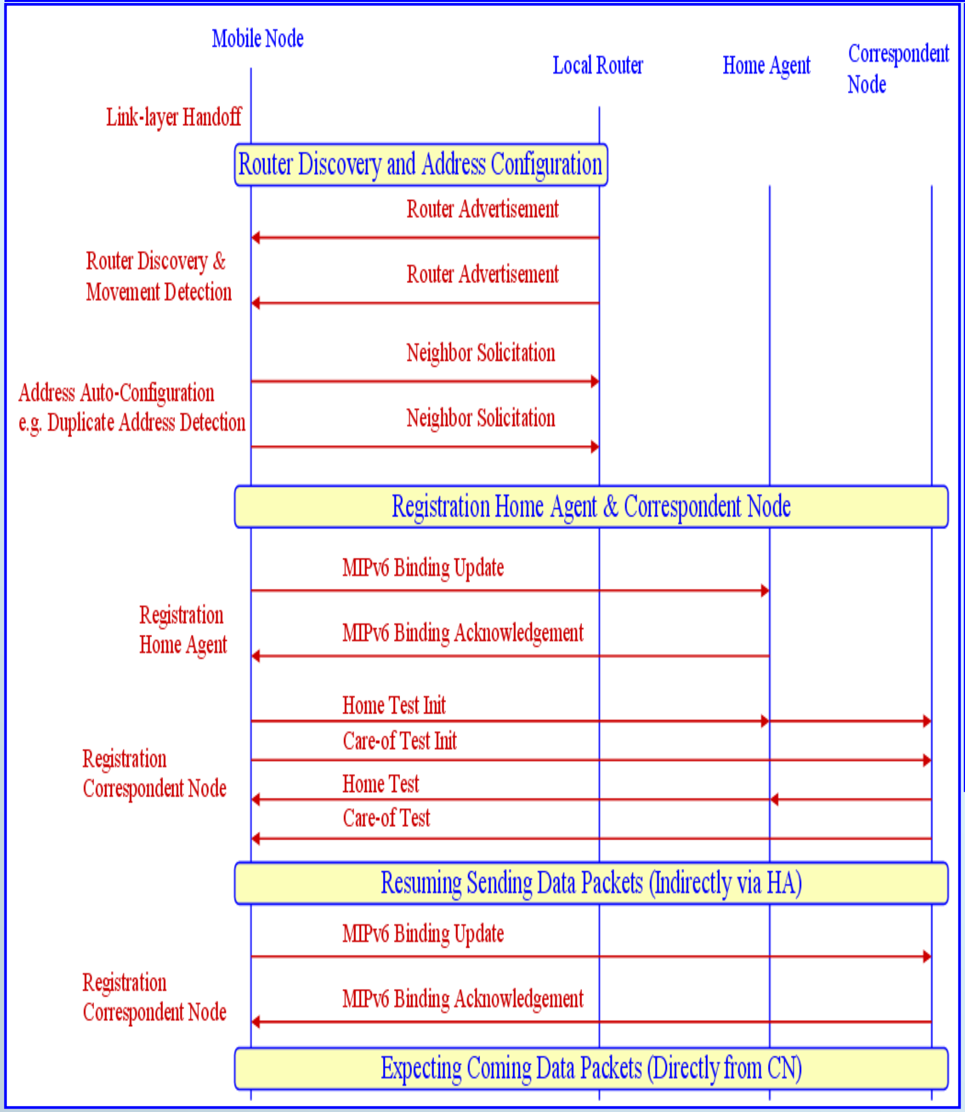


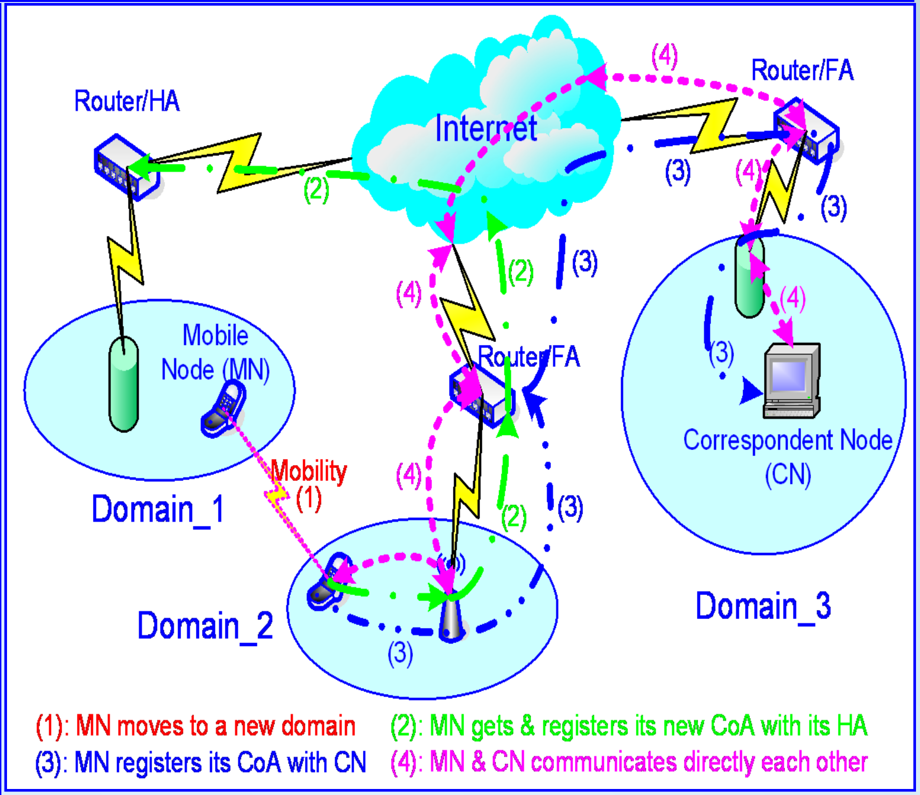


Co-Located Care-of Address

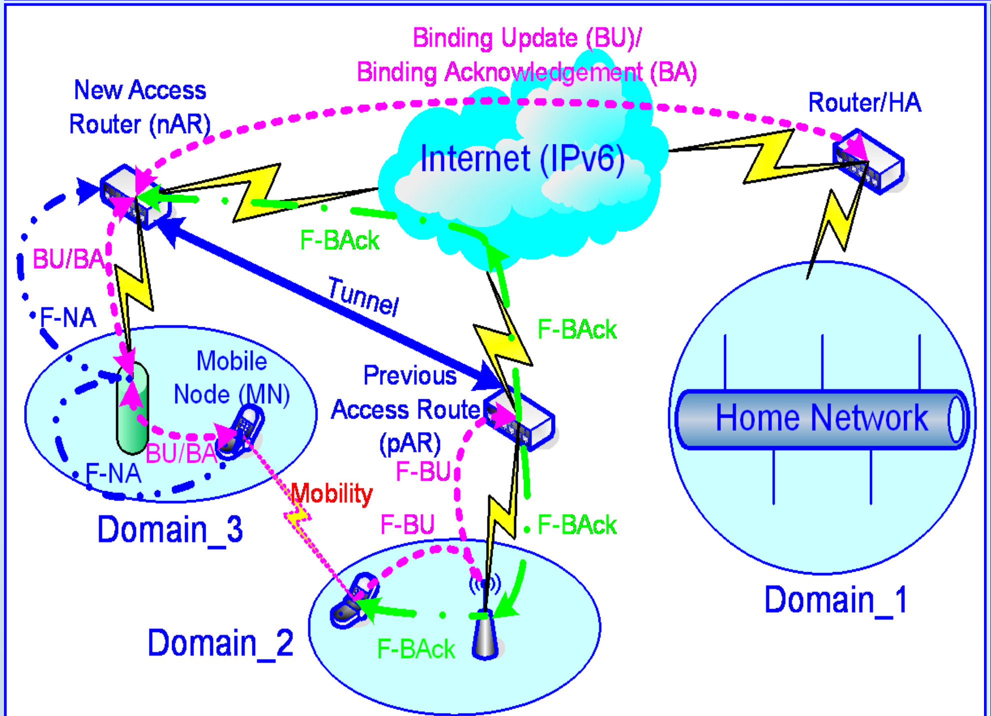


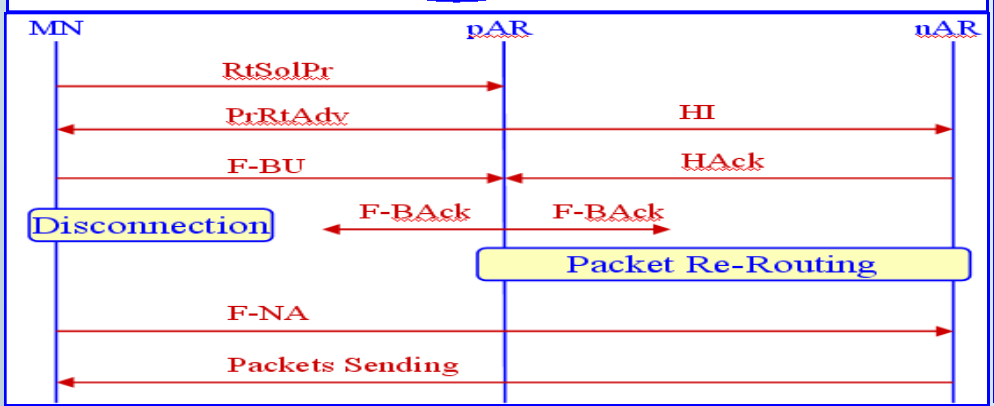
Review IP Mobility Management [MIPv6] (2/5)

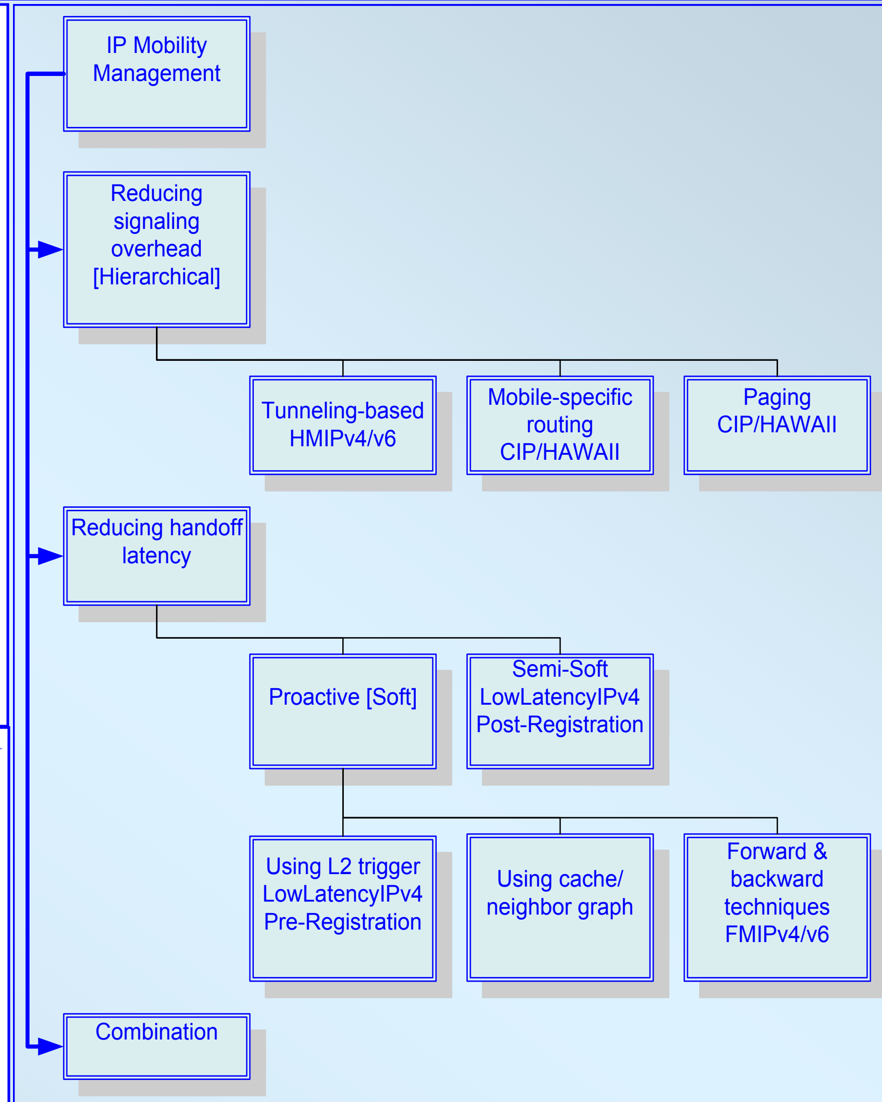




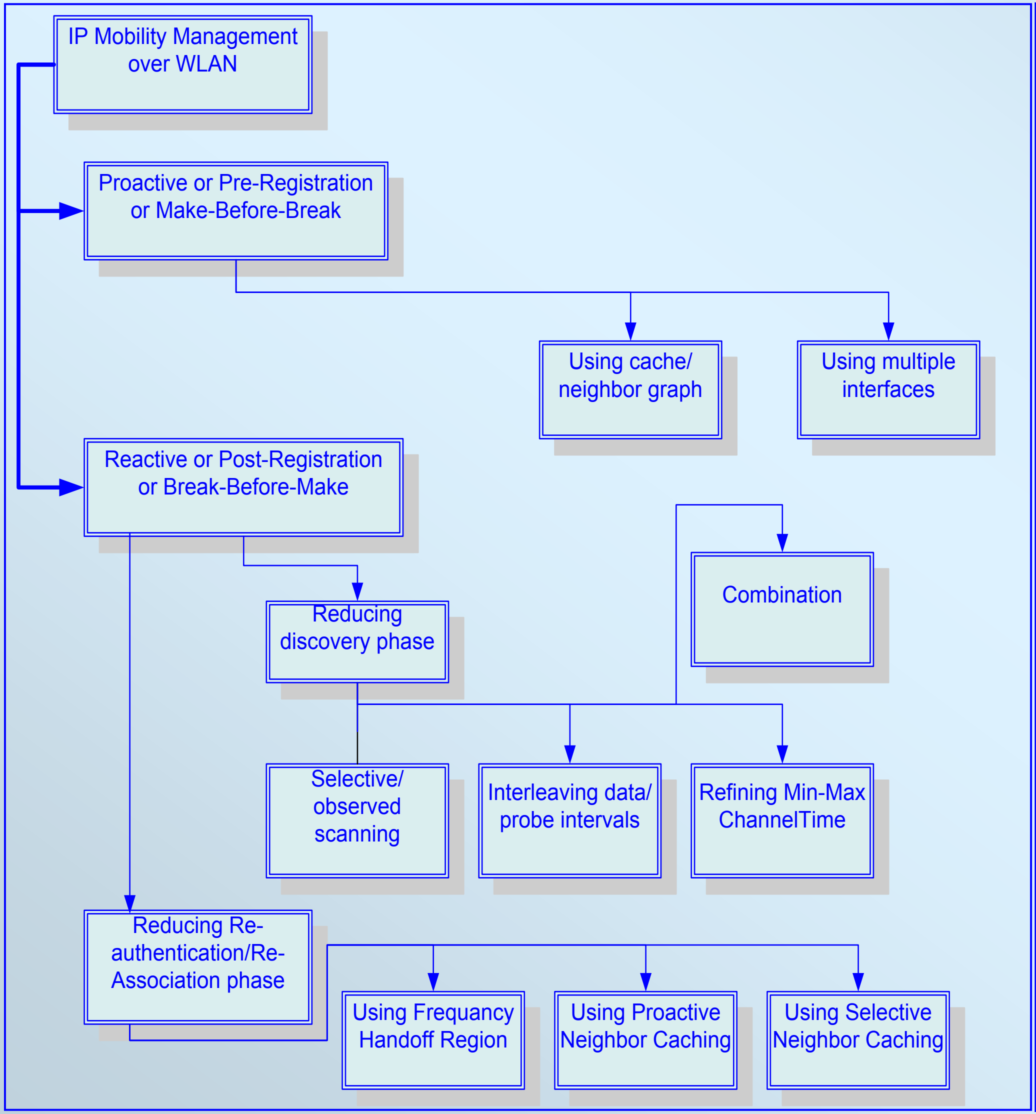
Review IP Mobility Management [FMIPv6] (3/5)

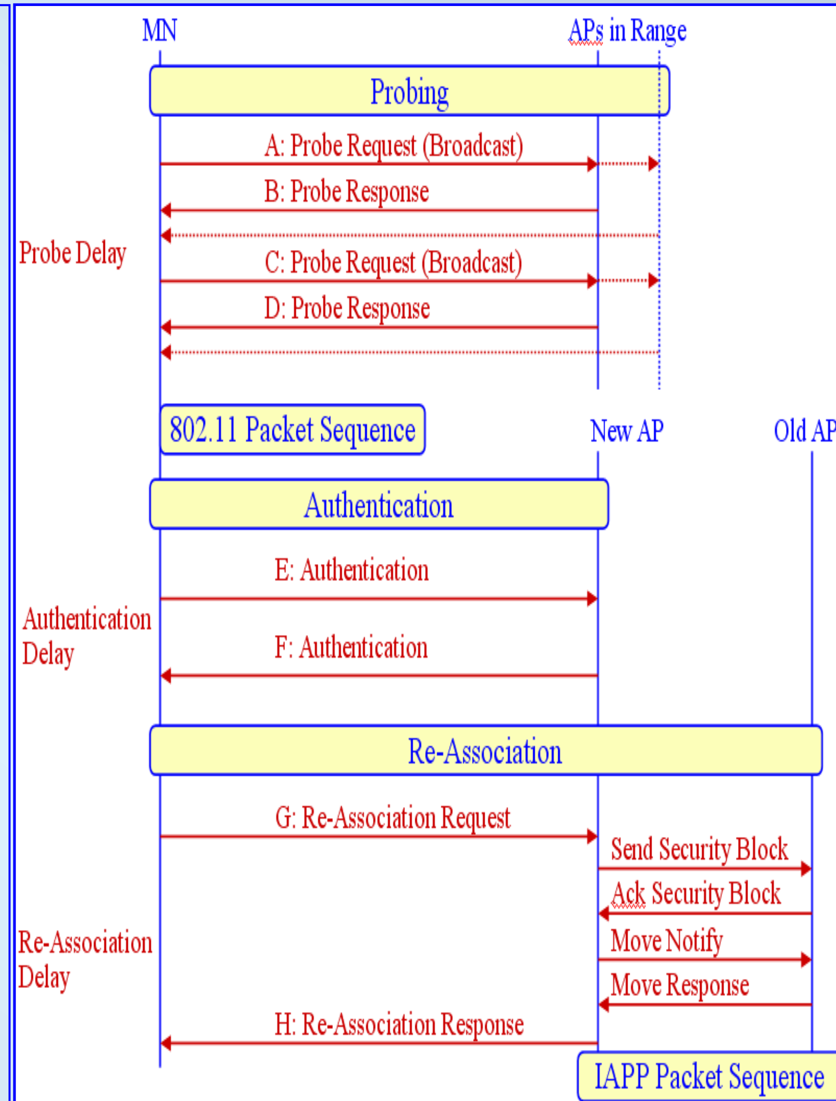






Review IP Mobility Management over WLAN (4/5)



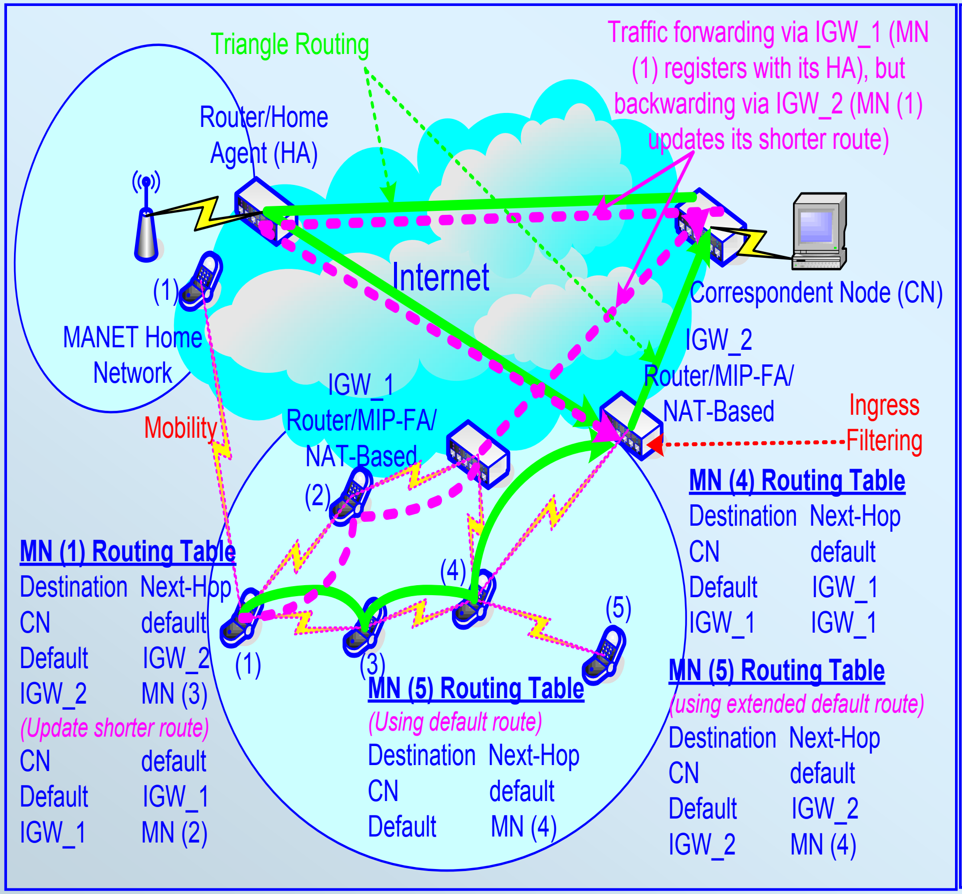


Review IP Mobility Management over MANET (5/5)

TABLE IX. COMPARISON BETWEEN DIFFERENT MECHANISMS FOR MANET INTERNET ACCESS AND MOBILITY MANAGEMENT

Index	Mechanism	Location determination	IGW discovery	IGW selection metrics	IGW forwarding	Addressing	Handoff style
1	MIPv6+ AODVv6 [66][210][211]	Network prefix	Proactive & reactive	Not specified, implicitly shortest hop-count	Default route & AODVv6 [13]	Deriving from IPv6 stateless auto-configuration	Both
2	MIPMANET [73]	Flooding RREQ	Proactive	Shortest hop-count	Half-tunneling & AODV [12]	Not specified, but Home Address must be IP global unicast	Route optimization-based
3	MIP+DSR [238]	Using IGW	Reactive	Not specified, implicitly shortest hop-count	Source routing & DSR [14]	Home Address must be IP global unicast	Not specified, implicitly route optimization-based
4	MIP+OLSR [173]	Using routing table	Proactive	Not specified, implicitly shortest hop-count	Default route & OLSR [18]	Not specified	Forced (when a prefix change)
5	MEWLANA TD/RD [187]	Using routing table (DSDV) or TBBR Tree	Proactive	Shortest hop-count	Default route & DSDV or TBBR	Not specified	Forced (when a route change or node leave)
6	Two-tier MANET [215]	Using routing table	Reactive	Load-balancing	Tunneling uses extra UDP/IP header & DSDV	Private address & NAT, allocating using DHCP	Not specified, implicitly route optimization-based
7	Hybrid MANET [172]	Using routing table	Reactive	Hybrid: Euclidean distance & load-balancing	Default route & DSDV [19]	Not specified	Forced (using automatic mode-detection and switching)
8	WLAN & MANET [170]	Using routing table	Proactive	Not specified, implicitly shortest hop-count	Default route & OLSR [18]	IPv6 stateless auto-configuration	Forced (using automatic mode-detection and switching)

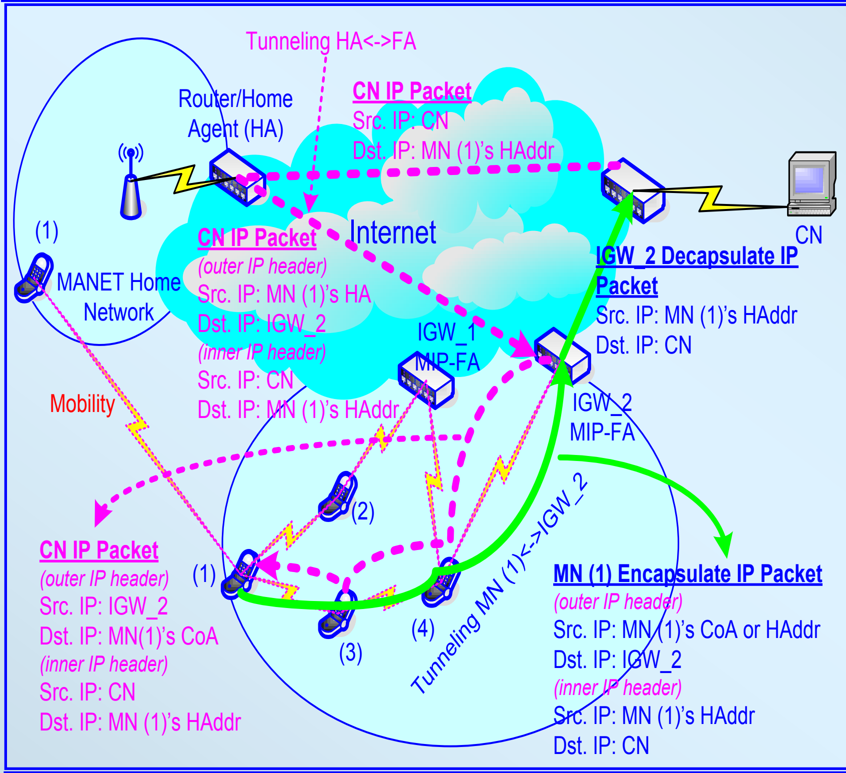
Discovered Problems on Internet Gateway Forwarding in MANET



- Inconsistent Context
  - Default Routing (Type I)
  - Default Routing (Type II)
  - Default Routing (Type III)
  - MIPv4-FA Triangle Routing
  - MIPv4-FA Ingress Filtering
- Cascading Effect in MANET Node Location Determination
- MIPv4-FA Traversing NAT

Quan Le-Trung, and Gabriele Kotsis (2008), "Reducing Inconsistent Context Problem on Providing Internet Connectivity for Mobile Ad Hoc Networks," *EuroFGI'08, LNCS Vol. 5122, ISBN: 978-3-540-89182-6*, Barcelona, Spain, Jan.2008, pp.113-127. [abstract]

Solutions on Internet Gateway Forwarding in MANET



- Inconsistent Context [IP-in-IP Tunneling]
  - Default Routing (Type I)
  - Default Routing (Type II)
  - Default Routing (Type III)
  - MIPv4-FA Triangle Routing
  - MIPv4-FA Ingress Filtering
- Cascading Effect in MANET Node Location Determination [Inserting IGW host route]
- MIPv4-FA Traversing NAT [IP-in MIP UDP-in IP tunneling]

Quan Le-Trung, and Gabriele Kotsis (2008), "Reducing Inconsistent Context Problem on Providing Internet Connectivity for Mobile Ad Hoc Networks," *EuroFGI'08, LNCS Vol. 5122, ISBN: 978-3-540-89182-6*, Barcelona, Spain, Jan.2008, pp.113-127. [abstract]

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A New Proposed Internet Gateway Selection Metric

$$Min\{w(i, j)\}_{j\in V_{IGW}} \quad (1)$$

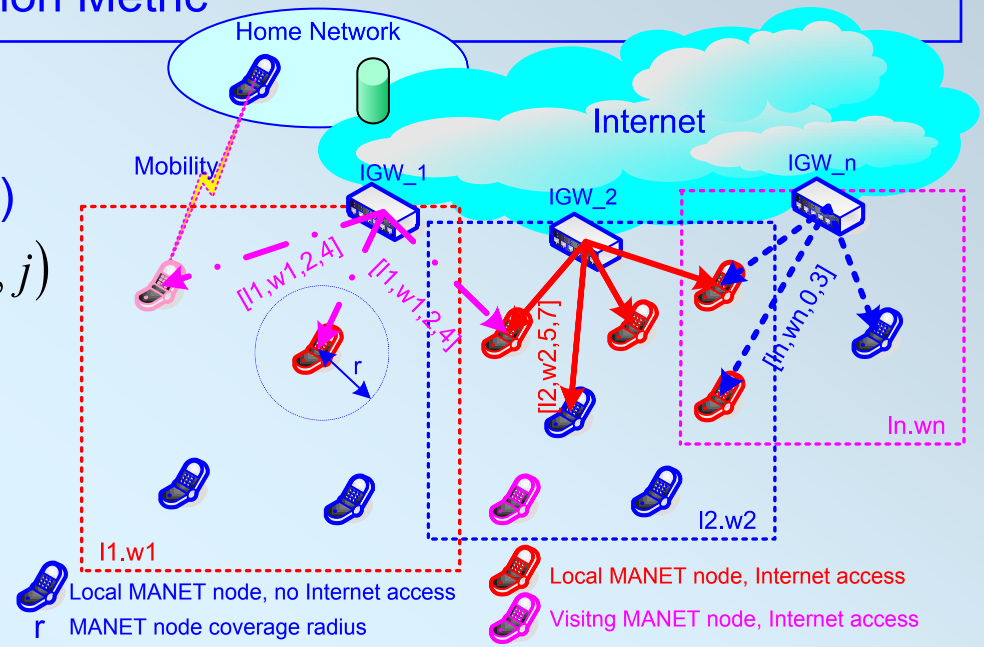
$$w(i, j)=\alpha_1.D(i, j)+\alpha_2.LB_{Internet}(j)+\alpha_3.LB_{MANET}(i, j) \quad (2)$$

$$\alpha_1+\alpha_2+\alpha_3=1 \quad (3)$$

$$LB_{Internet}(j)=n_{Reg}(j) \quad (4)$$

$$LB_{MANET}(i, j)=\begin{cases} 0 \quad \text{if} \quad ([AvgDeg(i, j)] \bmod \mathrm{K})=0 \\ \dfrac{1}{[AvgDeg(i, j)] \bmod \mathrm{K}}, \quad \text{otherwise} \end{cases} \quad (5)$$

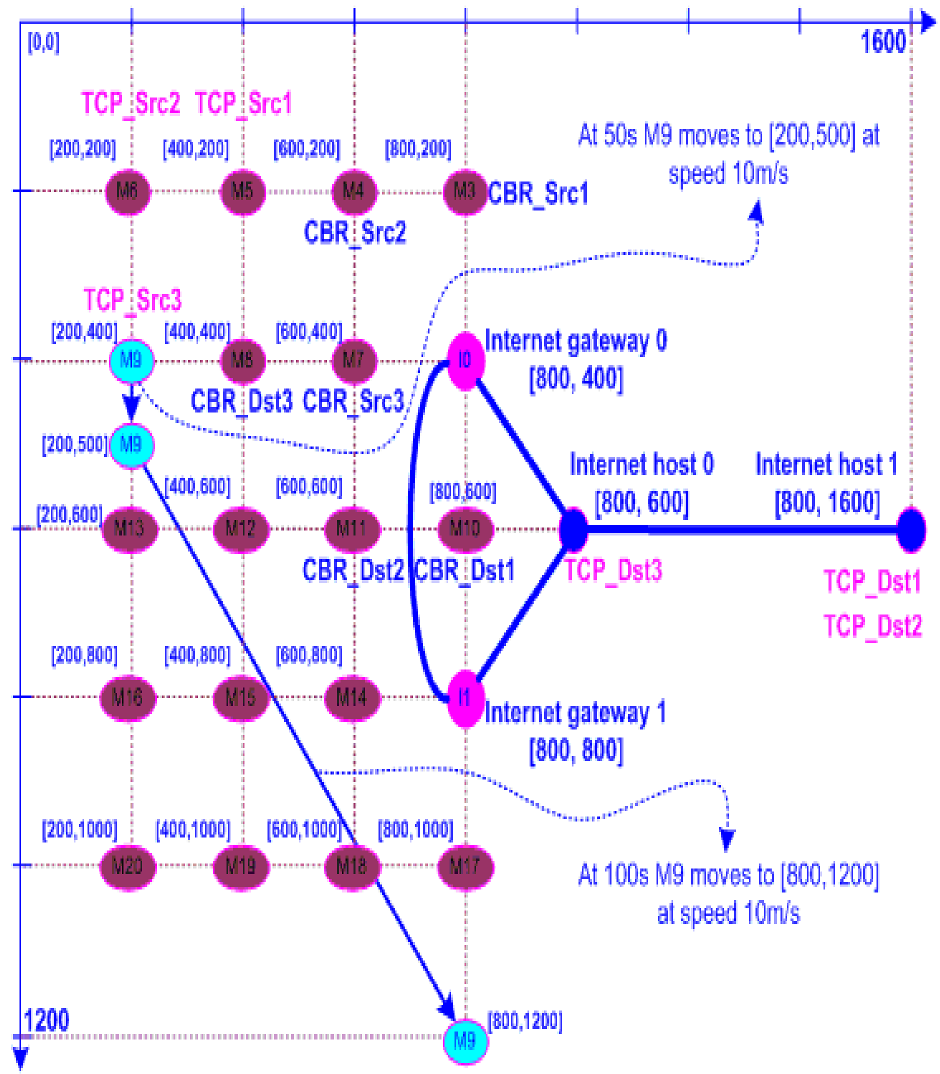
$$AvgDeg(i, j)=\begin{cases} \left(l_j.w_j-\dfrac{r.(l_j+w_j)}{2}+r^2\right).\dfrac{n_j.\pi.r^2}{(l_j.w_j)^2} & (\mathrm{i:local}) \\ \left(l_j.w_j-\dfrac{r.(l_j+w_j)}{2}+r^2\right).\dfrac{(n_j+1).\pi.r^2}{(l_j.w_j)^2} & (\mathrm{i:visited}) \end{cases} \quad (6)$$



- Objectives
  - Shortest Euclidean distance (hop-count)
  - Load-balancing Internet traffic [in/out]
  - Load-balancing Intra-MANET traffic

Simulation Scenarios & Performance Metrics

- **Packet delivery ratio**
  - ratio between total data packets sent by sources and total data packet received correctly by destinations **[%]**
- **Normalized signalling overhead**
  - ratio between the total number of packets carrying signalling information (including the ad hoc routing, the Internet gateway discovery, and the MIP registration), and the total number of data packets **[scalar]**
- **Average packet trans. delay**
  - average time of sending data packets from a particular ad hoc source to its associated Internet gateway **[sec] [Not shown here]**



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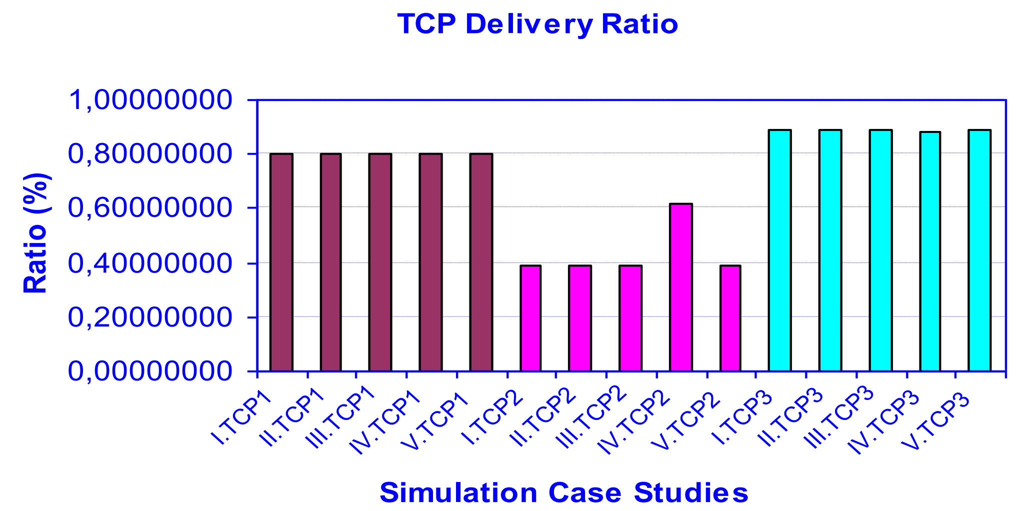
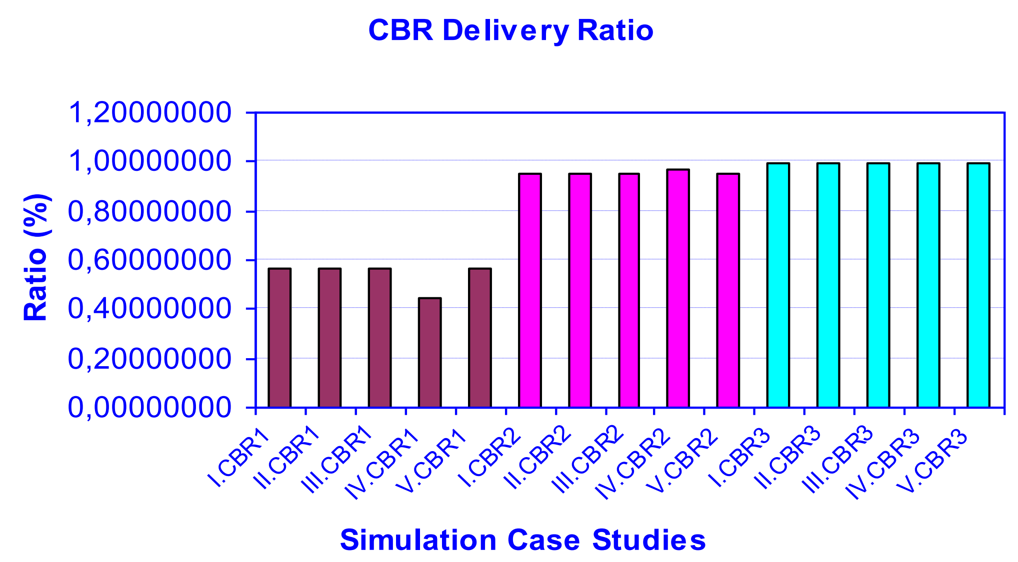
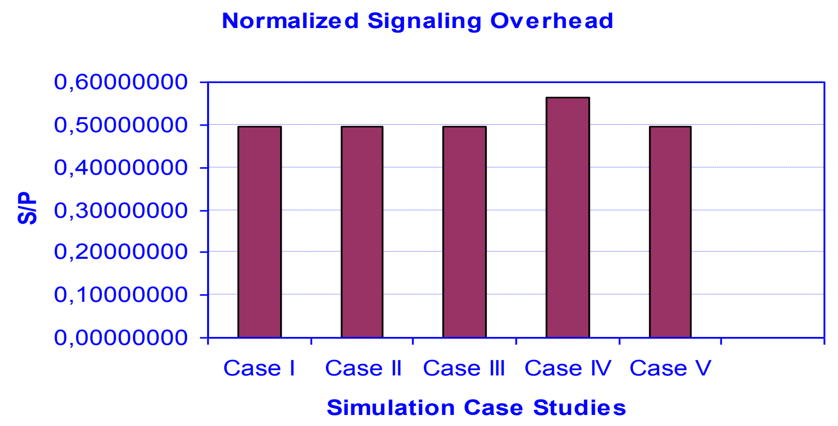
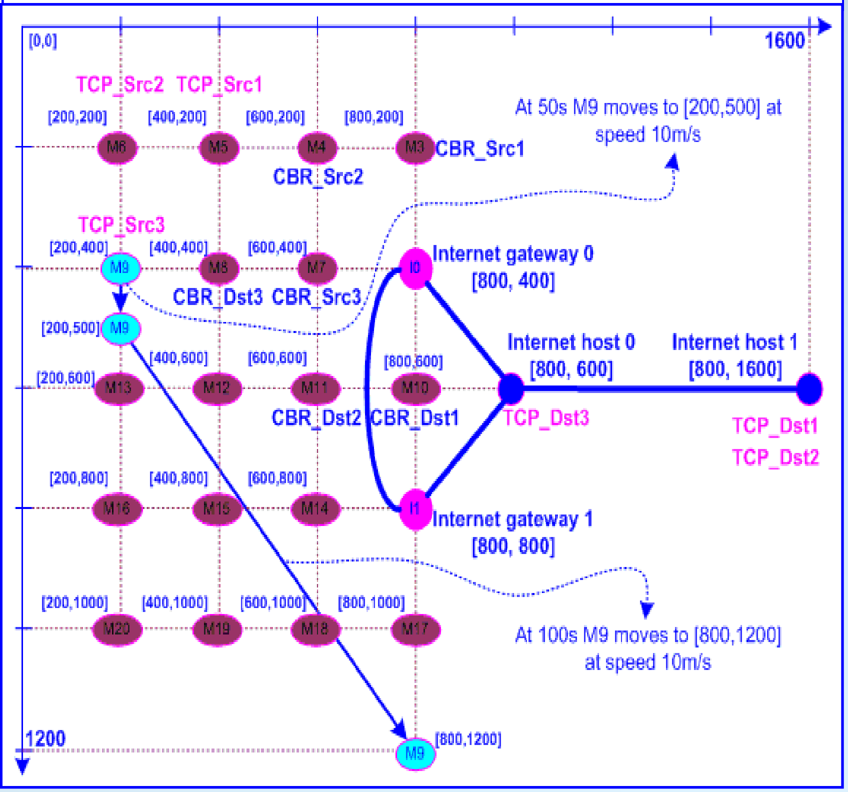
Simulation Results









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2. **Quan Le-Trung**, Paal E. Engelstad, Tor Skeie, and Amirhosein Taherkordi, (2008), "Load-Balance of Intra/Inter-MANET Traffic over Multiple Internet Gateways," *ACM MoMM'08 ISBN: 978-1-60558-269-6, Nov.24-26 2008*, Linz Austria, pp.50-57. [abstract]
3. **Quan Le-Trung**, and Gabriele Kotsis (2008), "Reducing Inconsistent Context Problem on Providing Internet Connectivity for Mobile Ad Hoc Networks," *EuroFGI'08, LNCS Vol. 5122, ISBN: 978-3-540-89182-6*, Barcelona, Spain, Jan.2008, pp.113-127. [abstract]
4. **Quan Le-Trung**, and Gabriele Kotsis, (2007) "Mobile Ad-Hoc Networks as the Access Networks for the Internet and Mobility Management," *EuroView2007*, Jul.23-24 2007, Würzburg, Germany. [abstract]
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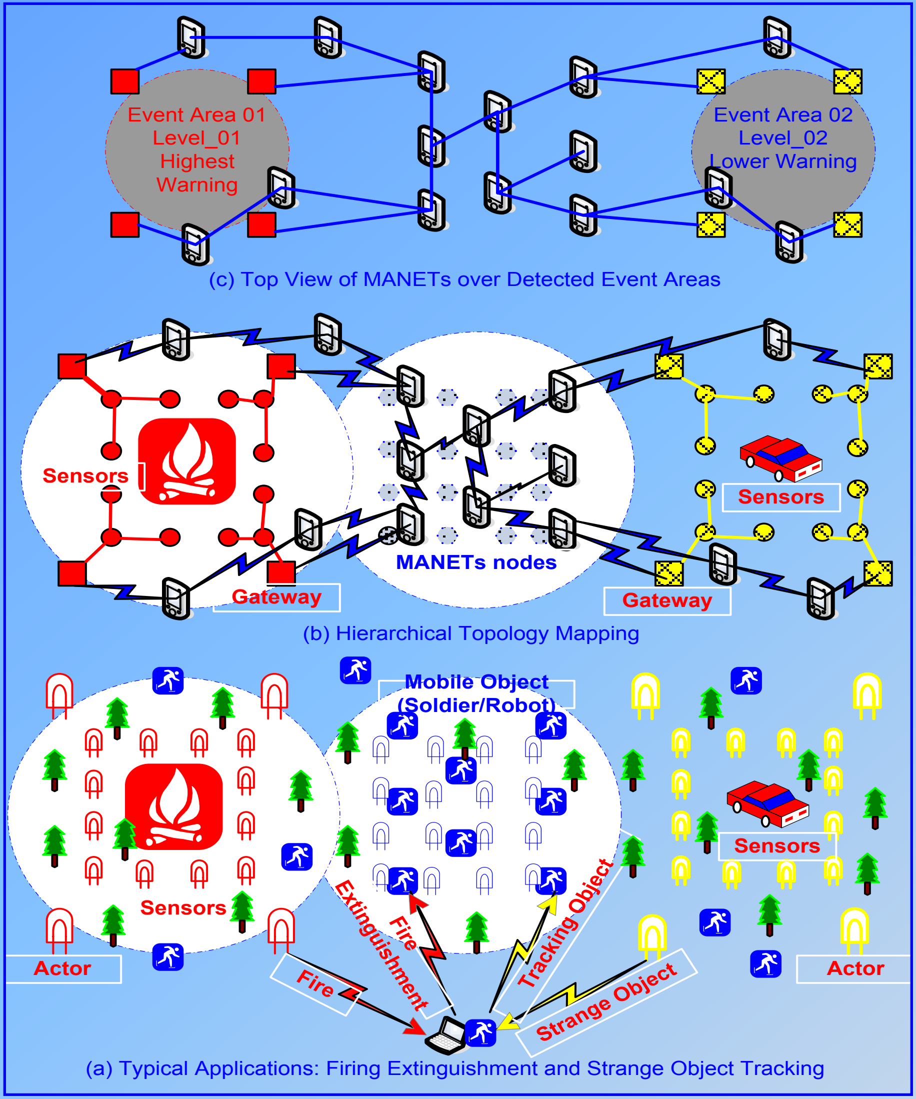
6. Vinh Pham, Erlend Larsen, **Quan Le-Trung**, Paal E. Engelstad, and Oivind Kure, (2011), "A Radio Load Based Load Balancing Scheme with Admission Control," *in the 6th IEEE International Symposium on Wireless Pervasive Computing (ISWPC), E-ISBN: 978-1-4244-9867-3, Print ISBN: 978-1-4244-9868-0*, Hong Kong-China, Feb.23-25 2011, pp.1-6. [abstract]

Formerly funded by CRUISE project: Creating Ubiquitous Intelligent Sensing Environment, FP6 NoE–IST-4-027738, *on the Application and Communication Aspects of Wireless Sensor Networking,* [01/2006-12/2007]

Collaboration MANETs/WSNs

Quan Le-Trung and Gabriele Kotsis (2008), “Arch-AdSenNets: An Architecture for Inter-Working MANET with Wireless Sensor and Actor Networks,” *International Journal of Communication Networks and Distributed Systems (IJCNDS)*, 2008 - Vol. 1, No.4/5/6 pp.466-506, Inderscience, ISSN (Online): 1754-3924 - ISSN (Print): 1754-3916. [abstract]

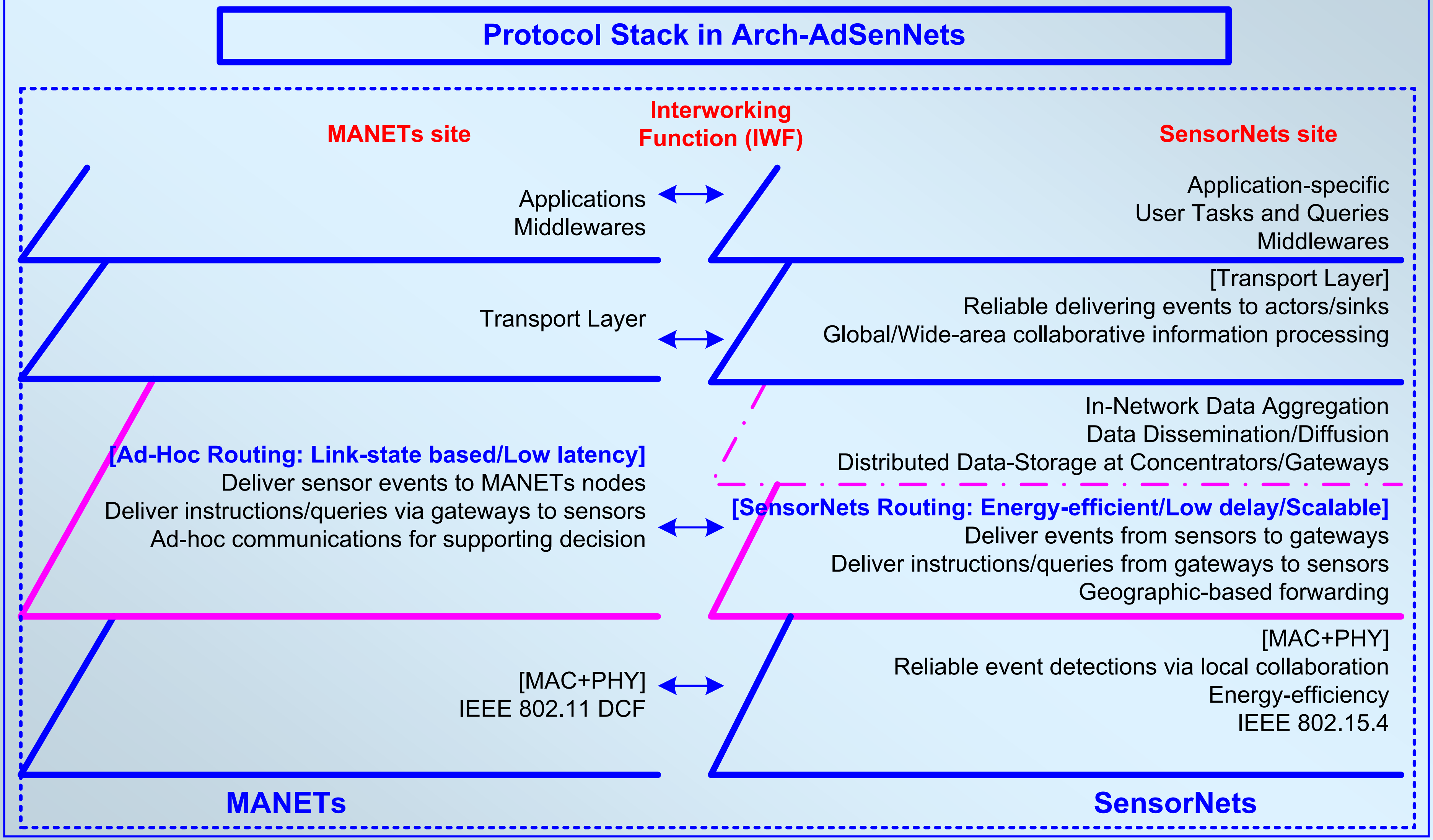
MANETs overlay over Wireless Sensor Networks



Objectives

- A framework, i.e. Arch-AdSenNets, for internetworking MANETs with WSANs
- A network model within above framework for MANET nodes and actors collaboration
- An implementation of distributed (heuristic) algorithms of network model into ns-2 (piggybacked over OLSR)

Arch-AdSenNets



Network Model [Objectives & Assumptions]

- Objectives
  - Maximizing resources of MANET nodes spend on processing detected events
  - Minimizing resources of MANET nodes spend on moving to areas of detected events
- Assumptions
  - Observation cycle T= $\sqrt{N_A}.\tau$
  - Action types of MANET nodes
    - Processing
    - Movement
    - Resource consumption rate is the same: [φ/sec]
      - **Objectives**

        Maximizing total processing time of MANET nodes on each observation cycle

        Minimizinh total moving time of MANET nodes on each observation cycle
  - Event weight is proportional to
    - Importance of event type
    - Scale of event [No. of source sensors detecting the event]
  - Network topology (l.w) is modeled as a grid
    - An actor is located centrally in each cell (DxD)
    - An actor has two interfaces
      - MANET (e.g. 802.11) for communicating with other actors/MANET nodes → instructing MANETs movements to event areas
      - Sensor (e.g. 802.15.4) for collecting sensor readings (detected events)

Network Model [Formulation of Optimized Problem]

Given:

$$V_M, V_A, V_S, V_{M/A}^{i-1}, E^i, E_T, \gamma_T, C, C_m^i, \varphi, T, l, w, D, v \qquad (1)$$

Find:

$$\forall A_j, A_n \in V_A, \forall m \in V_M, \forall e_m \in E^i : x^i_{jn/m}, y_j^{e_m}(i,m) \qquad (2)$$

Goal:

$$Max\{u^i\} = Max\left\{ \sum_{A_j \in V_A} \sum_{m \in V^i_{M/A_j}} \sum_{e_m \in E^i_j} y_j^{e_m}(i,m) \right\}, Min\{c^i\} = Min\left\{ \sum_{A_j \in V_A} \sum_{n \in V_A} \sum_{m \in V^{i-1}_{M/A_j}} d_{jn}.\tau.x^i_{jn/m} \right\} \qquad (3)$$

Subject to constraints:

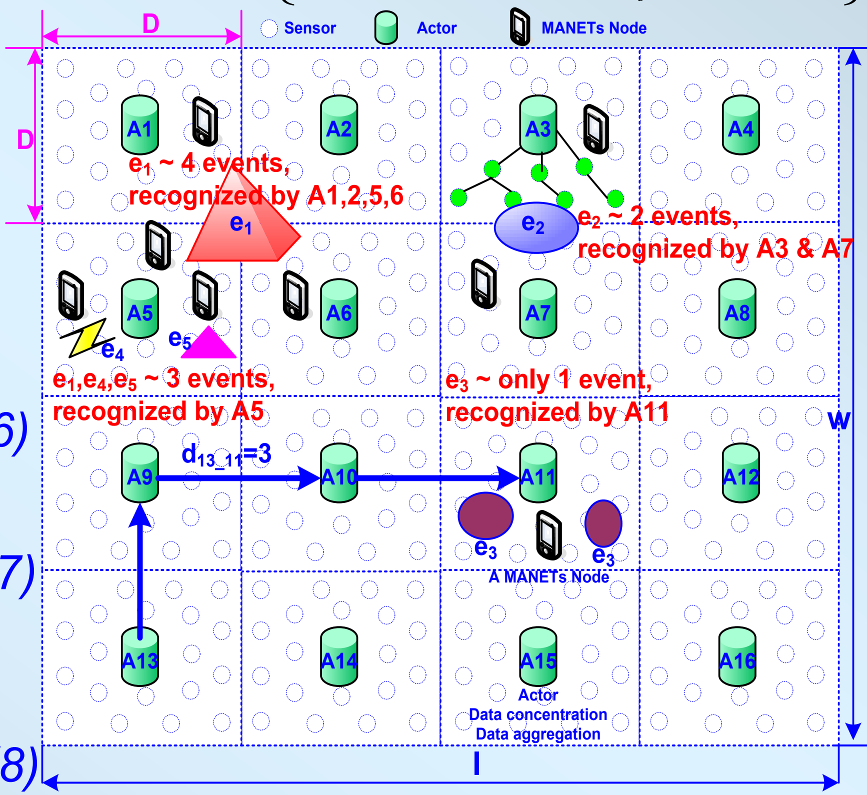
$$\forall A_j, A_n \in V_A, \forall m \in V_M : x^i_{jn/m} \in \{0,1\} \qquad (4)$$

$$\forall m \in V_M, \forall A_j \in V_A : \sum_{A_n \in V_A} x^i_{jn/m} \in \{0,1\} \qquad (5)$$

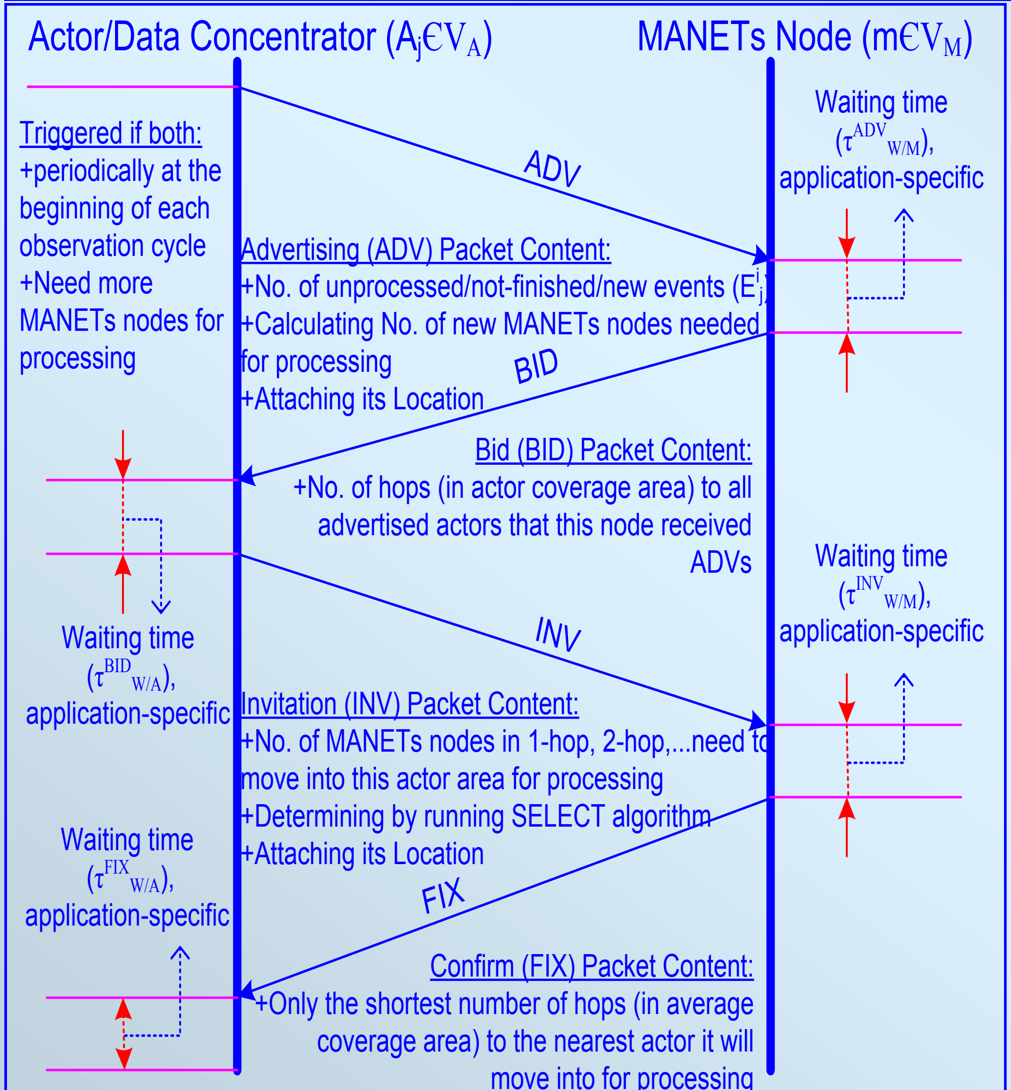
$$\forall A_j \in V_A, \forall m \in V_M, \forall e_m \in E^i : 0 \le \varphi.y_j^{e_m}(i,m) \le C_m^i \qquad (6)$$

$$\forall m \in V_M : \varphi.\left(\sum_{e_m \in E^i_j} y_j^{e_m}(i,m) + \sum_{n \in V_A} d_{jn}.\tau.x^i_{jn/m} \right) \le C_m^i \qquad (7)$$

$$\forall A_j \in V_A, e_m \in E^i_j : \left(\sum_{m \in V^i_{M/A_j}} y_j^{e_m}(i,m) \right) \le \tau_j^{e_m} \qquad (8)$$



Network Model [Distributed Algorithms]



Optimized Problem

Centralized

Solved by Micro-GA [See ref.]

Developing Distributed Algorithm

Setup Phase: Initial Allocation of MANETs achiving WPMM Fairness [Not shown here]

Negotiation Phase: Re-Allocation upon Appearance of New Events

Results

Pareto Optimal Set solved by Micro-GA

Simulation from ns-2

Results Comparison

- Theoretical (Numerical) Results
  - Solved by the micro-genetic algorithm [Micro-GA software]
  - Solutions are a set of possible optimal values, i.e. Pareto-Optimal Set
    - $\{Max\{u^i\}, Min\{c^i\}\}$, *i.e., {Utility, Cost}*
    - Increasing utility must compensate for increasing cost, and vice verse
      - Each point in Pareto-Optimal Set compared with to any other point:
        - » Either its utility is lower and its cost is lower, or
        - » Its utility is higher and its cost is higher
- Simulated Results
  - Taken from running negotiation phase in ns-2 in each observation cycle T
- Metric for testing is the "CONVERGENCE"
  - $Max\{u^i\}/Min\{c^i\}$ defines an lower/upper bound (threshold), respectively
  - **Convergence** If simulation values
    - Utility is higher, while cost is lower, than any point in Pareto Set
  - **Goodness of Convergence**
    - Compared with $Max\{Max\{u^i\}\}$, $Min\{Min\{c^i\}\}$, $Average\{Max\{u^i\},Min\{c^i\}\}$

Results Comparison

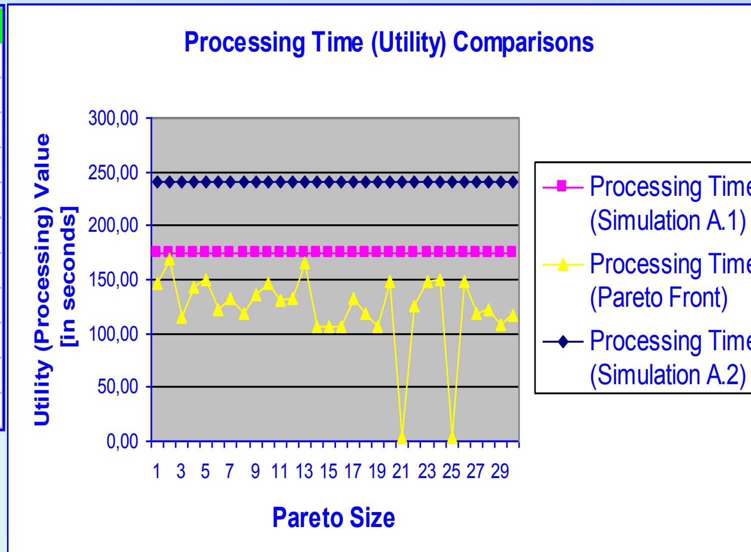
Pareto Optimal Set of Case Study I.A.1 (4Mx4Ax2E, 300mx300m, E1=120, E2=240)								
Pareto Index	f1	f2	Pareto Index	f1	f2	Pareto Index	f1	f2
1	146,7720	20,2192	11	130,1790	15,3375	21	3,5045	2,4234
2	168,4420	39,7239	12	131,8630	16,6826	22	125,3280	12,0443
3	114,9870	4,0083	13	166,3840	32,3222	23	148,0020	22,6147
4	143,4600	17,6040	14	106,2570	2,6645	24	149,9610	30,9826
5	149,8160	29,2169	15	106,0500	2,4556	25	2,8853	2,0787
6	121,8210	9,9069	16	106,4840	2,6648	26	148,2220	23,5467
7	132,3250	17,3226	17	133,3630	17,3240	27	118,1450	5,2503
8	118,2970	6,1573	18	118,3490	9,1049	28	122,1170	10,8179
9	136,7260	17,3602	19	107,0760	2,6674	29	108,4490	3,7492
10	147,0640	21,2162	20	148,0170	23,4860	30	116,0670	4,9773

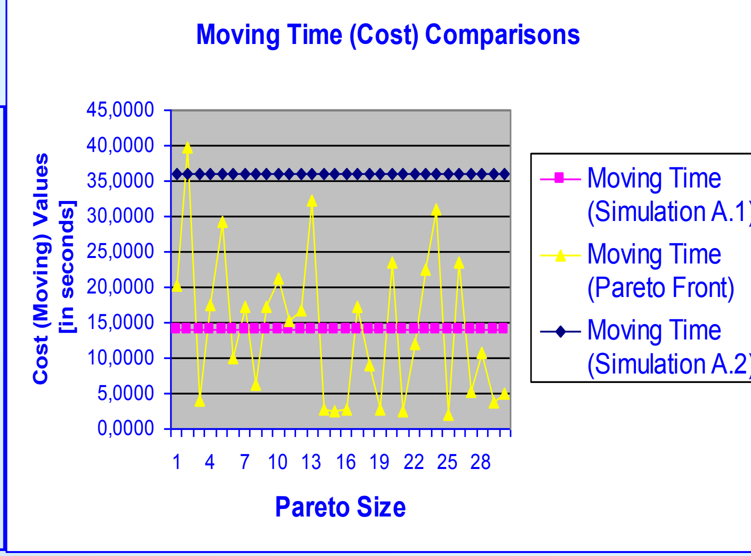
$$\max\{f_1(x_1,x_2,x_3,x_4,x_5,x_6,x_7,x_8,y_1,y_2,y_3,y_4,y_5,y_6,y_7,y_8)\}$$
$$\min\{f_2(x_1,x_2,x_3,x_4,x_5,x_6,x_7,x_8,y_1,y_2,y_3,y_4,y_5,y_6,y_7,y_8)\}$$
$$U = f_1 = (x_7.y_1 + x_8.y_3) + (x_4.y_4 + x_2.y_5 + x_5.y_7) + (x_1.y_2 + x_3.y_6 + x_6.y_8)$$
$$C = f_2 = \tau.(x_1 + x_4 + x_2 + x_3 + x_5 + x_6)$$

Constraints :

$$x_{i(1\le i\le 8)} \in \{0,1\}$$
$$0 \le y_{i(1\le i\le 8)} \le 2.\tau$$
$$0 \le (x_7.y_1 + x_1.y_2 + \tau.x_1) \le 2.\tau$$
$$0 \le (x_8.y_3 + x_4.y_4 + \tau.x_4) \le 2.\tau$$
$$0 \le (x_2.y_5 + \tau.x_2 + x_3.y_6 + \tau.x_3) \le 2.\tau$$
$$0 \le (x_5.y_7 + \tau.x_5 + x_6.y_8 + \tau.x_6) \le 2.\tau$$
$$0 \le (x_7.y_1 + x_4.y_4 + x_2.y_5 + x_5.y_7) \le 4.\tau$$
$$0 \le (x_1.y_2 + x_8.y_3 + x_3.y_6 + x_6.y_8) \le 8.\tau$$

Simulation Scenario [Case A]
+Four actors {A1, A2, A3, A4}
+Four MANET nodes for processing events {M1, M2, M3, M4}
+Topology (l=w=300m, D=150m), MANET node velocity (v=5 m/s)
+Time (τ=D/v=150/5=30 sec, observation cycle: T=2*τ=60 sec)
Event E1 in A1 (T1=4*τ=120 sec).
Event E2 in A2 (T2=8*τ=240 sec).





Results Comparison

First Simulation Scenario (4Mx4Ax2E, 300mx300m, E1=120 sec, E2=240 sec) A.1						
	FIX to Actor		Moving To		Moving Time [sec]	
MANETs	t^0	t^1	t^0	t^1	t^0	t^1
M1	A1	A2	_	_	0,0000	0,0000
M2	A1	A2	_	_	0,0000	0,0000
M3	A1	A2	_	A2	0,0000	14,1171
M4	A2	A2	_	_	0,0000	0,0000
Total					0,0000	14,1171
Processing Time of all MANETs nodes [sec]						
ACTOR	t^0			t^1		
A1			120,0000			0,0000
A2			55,0000			185,0000
A3			0,0000			0,0000
A4			0,0000			0,0000
Total			175,0000			185,0000
Finish at						110,0000

Initial Positions [Case A.1]

A1(75.0, 75.0) M1(5.0, 5.0)

A2(225.0, 75.0) M2(295.0, 5.0)

A3(75.0, 225.0) M3(5.0, 295.0)

A4(225.0, 225.0) M4(295.0, 295.0)

First Simulation Scenario (4Mx4Ax2E, 300mx300m, E1=120 sec, E2=240 sec) A.2						
	FIX to Actor		Moving To		Moving Time [sec]	
MANETs	t^0	t^1	t^0	t^1	t^0	t^1
M1	A2	A1	_	_	0,0000	0,0000
M2	A2	A1	_	A1	0,0000	10,6614
M3	A2	A1	_	A1	0,0000	11,9008
M4	A2	A1	_	A1	0,0000	13,5201
Total					0,0000	36,0823
Processing Time of all MANETs nodes [sec]						
ACTOR	t^0			t^1		
A1			0,0000			120,0000
A2			240,0000			0,0000
A3			0,0000			0,0000
A4			0,0000			0,0000
Total			240,0000			120,0000
Finish at						105,0000

Initial Positions [Case A.2]

A1(75.0, 75.0) M1(5.0, 295.0)

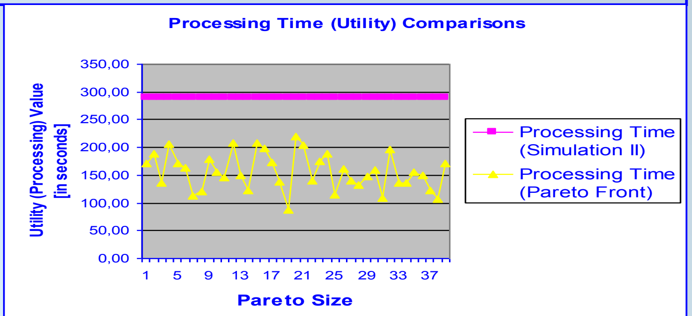
A2(225.0, 75.0) M2(285.0, 285.0)

A3(75.0, 225.0) M3(290.0, 290.0)

A4(225.0, 225.0) M4(295.0, 295.0)

Results Comparison

Pareto Optimal Set of Case Study II.B (6Mx6Ax2E, 450mx300m, E1=240, E2=240)								
Pareto Index	f1	f2	Pareto Index	f1	f2	Pareto Index	f1	f2
1	170,3140	75,4491	16	197,4480	136,8590	31	109,4260	28,4954
2	189,4500	97,4712	17	173,5770	79,5205	32	196,1940	127,1250
3	135,7140	40,5896	18	138,3870	49,8359	33	136,3720	42,6699
4	206,7250	144,3520	19	87,6299	24,8623	34	136,6020	46,9748
5	170,3110	73,5984	20	219,2940	155,6000	35	155,1980	60,1836
6	162,8770	66,9530	21	204,9510	140,7460	36	150,5550	59,4745
7	113,6560	29,1986	22	140,1180	50,8996	37	123,3760	32,6779
8	120,4930	31,7080	23	175,3090	84,9543	38	106,0770	27,3455
9	179,1740	89,0337	24	188,3040	96,5337	39	170,3130	75,4482
10	156,2040	62,9605	25	114,0960	31,2713			
11	146,7880	52,2571	26	161,2080	65,4489			
12	207,8760	154,4150	27	139,3290	50,6420			
13	149,7290	56,4932	28	132,5180	40,4123			
14	123,3380	31,9656	29	147,2020	56,0490			
15	207,9470	154,6640	30	159,0360	63,8082			



$$\max\{f_1(x_1,x_2,x_3,x_4,x_5,x_6,x_7,x_8,x_9,x_{10},x_{11},x_{12},y_1,y_2,y_3,y_4,y_5,y_6,y_7,y_8,y_9,y_{10},y_{11},y_{12})\}$$

$$\min\{f_2(x_1,x_2,x_3,x_4,x_5,x_6,x_7,x_8,x_9,x_{10},x_{11},x_{12},y_1,y_2,y_3,y_4,y_5,y_6,y_7,y_8,y_9,y_{10},y_{11},y_{12})\}$$

$$U = f_1 = (x_7.y_1 + x_8.y_3) + (x_4.y_4 + x_2.y_5 + x_5.y_7 + x_9.y_9 + x_{11}.y_{11}) + (x_1.y_2 + x_3.y_6 + x_6.y_8 + x_{10}.y_{10} + x_{12}.y_{12})$$

$$C = f_2 = \tau.(x_1 + x_4 + x_2 + x_3 + x_5 + x_6) + 2.\tau.(x_9 + x_{10} + x_{11} + x_{12})$$

Constraints :

$$x_{i(1\le i\le 12)} \in \{0,1\}$$

$$0 \le y_{i(1\le i\le 12)} \le 2.\tau$$

$$0 \le (x_7.y_1 + x_1.y_2 + \tau.x_1) \le 2.\tau$$

$$0 \le (x_8.y_3 + x_4.y_4 + \tau.x_4) \le 2.\tau$$

$$0 \le (x_2.y_5 + \tau.x_2 + x_3.y_6 + \tau.x_3) \le 2.\tau$$

$$0 \le (x_5.y_7 + \tau.x_5 + x_6.y_8 + \tau.x_6) \le 2.\tau$$

$$0 \le (x_9.y_9 + 2.\tau.x_9 + x_{10}.y_{10} + 2.\tau.x_{10}) \le 2.\tau$$

$$0 \le (x_{11}.y_{11} + 2.\tau.x_{11} + x_{12}.y_{12} + 2.\tau.x_{12}) \le 2.\tau$$

$$0 \le (x_7.y_1 + x_4.y_4 + x_2.y_5 + x_5.y_7 + x_9.y_9 + x_{11}.y_{11}) \le 8.\tau$$

$$0 \le (x_1.y_2 + x_8.y_3 + x_3.y_6 + x_6.y_8 + x_{10}.y_{10} + x_{12}.y_{12}) \le 8.\tau$$

Simulation Scenario [Case B]

+Six actors {A1,A2,A3,A4,A5,A6}
+Six MANET nodes for processing events {M1, M2, M3, M4, M5, M6}
+Topology (l=450m, w=300,D=150m)
+MANET node velocity (v=5 m/s)
+Time (τ=D/v=150/5=30 sec, observation cycle: T=2*τ=60 sec)
+Event E1 in A1 (T1=8*τ=240 sec)
+Event E2 in A2 (T2=8*τ=240 sec)
+A1(75,75), A2(225,75), A3(75,225), A4(225,225), A5(75,375), A6(225,375)
+M1(5,5), M2(295,5), M3(5,295), M4(295,295), M5(5,445), M6(295,445)

Second Simulation Scenario (6Mx6Ax2E, 450mx300m, E1=240 sec, E2=240 sec)						
	FIX to Actor		Moving To		Moving Time [sec]	
MANETs	t^0	t^1	t^0	t^1	t^0	t^1
M1	A2	A1	_	A1	0,0000	2,4823
M2	A2	A1	_	A1	0,0000	2,4823
M3	A1	A1	_	_	0,0000	0,0000
M4	A2	A1	_	A1	0,0000	12,8887
M5	A2	A1	A2	A1	37,0907	2,4823
M6	A2	A1	A2	A1	26,5108	0,6402
Total					63,6015	20,9758

Processing Time of all MANETs nodes [sec]		
ACTOR	t^0	t^1
A1	60,0000	180,0000
A2	230,0000	10,0000
A3	0,0000	0,0000
A4	0,0000	0,0000
A5	0,0000	0,0000
A6	0,0000	0,0000
Total	290,0000	190,0000
Finish at		100,0000

Results Comparison

- utility values of simulation are always larger than those of *max{max{f1}}*
- cost values of simulation are always lower than those of *max{max{f1}}*
  - the simulation results converge to the theoretical optimal results (Pareto optimal set) solved by the Micro-GA.

Values	Theoretical optimal values solved by the Micro-GA						Simulation	
	max{max{*f1*}} case		min{min{*f2*}} case		avg{max{f1},min{f2}} case			
	Utility	Cost	Utility	Cost	Utility	Cost	Utility	Cost
Case study I.A.1	168,4420	39,7239	2,8853	2,0787	122,5471	14,1977	175,0000	14,1000
Case study I.A.2	168,4420	39,7239	2,8853	2,0787	122,5471	14,1977	240,0000	36,0000
Case study I.B	188,7400	44,3693	59,7567	4,0740	142,3449	18,2209	240,0000	13,8165
Case study II	219,2940	155,6000	87,6299	24,8623	156,4902	71,5115	290,0000	63,6105

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2. **Quan Le-Trung**, and Gabriele Kotsis, (2007) "A Network Model for MANET Nodes and Actors Collaboration to Optimize Processing in Event Areas," *ACMSIG PEWASUN'07*, Chania, Crete Island, Greece, October 22-26, 2007. [abstract]

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