Research Areas in Mobile Ad-Hoc Networks

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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


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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

Solutions mostly for Standalone MANET!

Source: (Chris Ellis, Dec.2004)

Source: (Seoung-Bum Lee, 2000)
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

Cross Layer Model

Arch-InterMANETs

the MANETs site
- Native MANETs Applications
- New Internet-NGI Applications
- Legacy Internet Applications
- Middleware
- MANETs application security

MAC QoS support using
- Reservation Reservation
- SRMA/PA
- MANETs security at MAC layer

Network Layer
- Hybrid Hierarchical QoS Routing
- BGP-GCR+
- MANETs security network layer

Interworking Function (IWF)
- Middleware (i3)
- security

Interworking
- New Internet-NGI Applications
- Legacy Internet Applications
- Middleware
- security

the Internet site
- New Internet-NGI Applications
- Legacy Internet Applications
- Middleware
- security

TCP
- TCP Flow
- security

SSL
- TCP

IP Routing
- Constraint-based Routing
- IPsec

MPLS/GMPLS
- ATM/SONET-SDH/DWDM

Middleware
- security

Native MANETs Applications
- New Internet-NGI Applications
- Legacy Internet Applications
- Middleware
- MANETs application security

TCP/ATCP
- MANETs security transport layer

Network Layer
- Hybrid Hierarchical QoS Routing
- BGP-GCR+
- MANETs security network layer

MAC QoS support using
- Reservation Reservation
- SRMA/PA
- MANETs security at MAC layer

End-to-end Flow
- QoS MIP+MPLS, security

MIP/DHMIP/SIP, Mobile IP Security (MolPS), IPv6
+ addressing, routing + security, mobility, QoS
MANETs as Transit Networks for the Internet

### 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, rfc5s)

#### 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
### 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 ($R_{\text{max}}$), 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

### A summary of the characteristics of GCR

<table>
<thead>
<tr>
<th>Items</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clustering</td>
<td>Two-level</td>
</tr>
<tr>
<td>Cluster head election degree</td>
<td>Local (R=1) maximum degree</td>
</tr>
<tr>
<td>Cluster maintenance</td>
<td>One-node fault-tolerant Anti-fluctuations based on Gravitational clustering and node stability</td>
</tr>
<tr>
<td>Broadcast range</td>
<td>$R_{\text{max}}$</td>
</tr>
<tr>
<td>Overlapped area</td>
<td>No</td>
</tr>
<tr>
<td>QoS support</td>
<td>Yes</td>
</tr>
<tr>
<td>Address assignment</td>
<td>Assumption assigned (any methods)</td>
</tr>
<tr>
<td>Area of application</td>
<td>Large-scale, dense MANETs</td>
</tr>
<tr>
<td>Space complexity of cluster head</td>
<td>$O(n^<em>\text{AvgDeg(n)}+N_{\text{cluster}}^</em>\text{AvgDeg(n)}+\text{AvgDeg(n)})$</td>
</tr>
<tr>
<td>Time complexity of cluster head</td>
<td>$O(f(n^<em>\text{AvgDeg(n)}+N_{\text{cluster}}^</em>\text{AvgDeg(n)}+\text{AvgDeg(n)})$</td>
</tr>
<tr>
<td>Space complexity of others</td>
<td>$O(\text{AvgDeg(n)})$</td>
</tr>
<tr>
<td>Time complexity of others</td>
<td>$O(f(\text{AvgDeg(n)}))$</td>
</tr>
</tbody>
</table>
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+ consists of:

- QoS Routing Protocol
- Address Auto-Configuration
- Selection Procedure at internet gateways

Current Implementation of BGP-GCR+:

- QoS Routing Protocol for large-scale ad-hoc networks

Node Entry

Layer-Architecture of Mobile Node in NS-2

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

**Sending JOIN/LN**

- **t = 0**
  - Send JOIN/LN

- **t = 1*ζ**, forward
  - \( A_{R-1} \rightarrow A_{s} \)

- **t = (R_Max-1)*ζ**, forward
  - \( A_{s} \rightarrow B_{0} \)

- **t = T0 = R_Max*ζ**
  - \( A_{s} \rightarrow C_{d} \)

- **t = T0**
  - \( C_{0} \) to \( C_{d} \)

**Receiving JOIN/LN**

- **t = T0**
  - \( A_{s} \rightarrow C_{d} \)

- **RTT = 2*n*Avg_PerHopTime**

- **Max_RTT = 2*N*Avg_PerHopTime**

- **N: Network Diameter**

- **InterRouteCache_LifeTime = μ*Max_RTT**

**Routing Calculation**

- \( T_0 = \alpha.\zeta.R_{\text{Max}} \) (0 ≤ \( \alpha \) ≤ 1)

- \( \zeta : \text{Avg}_\text{PerHopTime}, \ r : \text{Coverage radius} \)

- \( T_1 = \frac{\bar{d}}{s} = \beta.\frac{2r}{s} \) (0 ≤ \( \beta \) ≤ 1) → \( T_1 \geq T_0 \)

**Additional Notes**

- Coverage range: \( r \), \( \alpha \), \( \zeta \), \( \beta \)

- Roaming out of \( A_{R-1} \) range

- Link Broken → send JOIN/LN
Determining Time Intervals: Broadcasting, Updating Caches, Lifetime

\[ T_0 = \alpha \cdot I_{N-Update-Fixed} \cdot R_{Max} \cdot Avg_{PerHopTime} \quad (\alpha \leq 1, R_{Max}: \text{cluster radius}) \quad (1) \]

\[ T_1 = \left( \frac{a \cdot r}{\text{Max\{speed\}}} \right) (r: \text{node coverage radius, } 0 \leq a \leq 2, \text{Average: } \bar{a} = 1) \quad (2) \]

\[ T_0 \leq T_1 \iff I_{N-Update-Fixed} \leq \left( \frac{a \cdot r}{\text{Max\{speed\}}} \right) \cdot \frac{1}{R_{Max} \cdot Avg_{PerHopTime}} \quad (3) \]

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

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

\[ \rightarrow I_{N-Lifetime} = \left[ 1.5 \cdot \text{ALLOWED HELLO LOSS} \cdot I_{N-Update-Fixed} \right] \quad (6) \]

\[ I_{R-Lifetime} = \mu_1 \cdot Max_{RTT} = \mu_1 \cdot 2 \cdot N \cdot Avg_{PerHopTime} \quad (N: \text{Network Diameter}) \quad (7) \]

\[ I_{R_Update} = \mu_2 \cdot Max_{RTT} \quad (\mu_1 \geq 1, 1 \geq \mu_2 \geq 0.5) \quad (8) \]
Multiple routes for Load-Balancing or Backup for A7

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

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

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


Mobility Management in All-IP Mobile Networks

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

- Mobile Node
  - Link-layer Connectivity
  - Agent Solicitation
  - Agent Advertisement
  - Registration
    - MIPv4 Registration Request
    - MIPv4 Registration Reply

- Foreign Agent

- Home Agent
  - Link-layer Connectivity
  - Agent Solicitation
  - Agent Advertisement
  - Registration
    - MIPv4 Registration Request
    - MIPv4 Registration Reply

Gateways

Co-Located Care-of Address

(1): MN moves to a new domain
(2): MN gets & registers its new CoA with its HA
(3): MN sends data directly to CN
(4): CN sends data to MN indirectly via MN's HA
(5): MN's HA tunnels data to MN's FA
(6): MN's FA delivers data to MN
### IP Mobility Management [MIPv6] (2/5)

**Link-layer Handoff**
- Mobile Node
  - Router Discovery and Address Configuration
    - Router Advertisement
    - Neighbor Solicitation
- Router Discovery & Movement Detection
  - Router Advertisement
  - Neighbor Solicitation

**Address Auto-Configuration e.g. Duplicate Address Detection**
- Mobile Node
  - Neighbor Solicitation

**Registration Home Agent & Correspondent Node**
- Mobile Node
  - MIPv6 Binding Update
  - MIPv6 Binding Acknowledgement
  - Home Test Init
  - Care-of Test Init
  - Home Test
  - Care-of Test
- Correspondent Node
  - Resuming Sending Data Packets (Indirectly via HA)
  - MIPv6 Binding Update
  - MIPv6 Binding Acknowledgement
  - Expecting Coming Data Packets (Directly from CN)

**Diagram**
1. Mobile Node (MN) moves to a new domain
2. MN gets & registers its new CoA with its HA
3. MN registers its CoA with CN
4. MN & CN communicate directly each other
Reducing signaling overhead [Hierarchical]

Reducing handoff latency

Proactive [Soft]

Semi-Soft LowLatencyIPv4 Post-Registration

Using L2 trigger LowLatencyIPv4 Pre-Registration

Using cache/neighbor graph

Forward & backward techniques FMIPv4/v6

Combination

IP Mobility Management

Tunneling-based HMIPv4/v6

Mobile-specific routing CIP/HAWAI

Paging CIP/HAWAI

MN

RtSolPr

PrRtAdv

F-BU

Disconnection

Packet Re-Routing

Packet Sending

nAR

Router/HA

Router/HA

New Access Router (nAR)

Previous Access Router (pAR)

Home Network

Domain_1

Domain_2

Domain_3

F-BAck

F-NA

F-BAck

F-BAck

F-BAck

Internet (IPv6)
Review: IP Mobility Management over WLAN (4/5)

Proactive or Pre-Registration or Make-Before-Break

- Using cache/neighbor graph
- Using multiple interfaces

Reactive or Post-Registration or Break-Before-Make

- Reducing discovery phase
- Selective/observed scanning
- Interleaving data/probe intervals
- Refining Min-Max ChannelTime

Using Frequency Handoff Region
Using Proactive Neighbor Caching
Using Selective Neighbor Caching

Combination

IP Mobility Management over WLAN

Probing:
A: Probe Request (Broadcast)
B: Probe Response
C: Probe Request (Broadcast)
D: Probe Response

802.11 Packet Sequence

Authentication:
E: Authentication
F: Authentication

Re-Association:
G: Re-Association Request
H: Re-Association Response

Send Security Block
Ack Security Block
Move Notify
Move Response

IAPP Packet Sequence

APs in Range

New AP
Old AP
### Comparison between different mechanisms for MANET Internet access and mobility management

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<th>Location-determination</th>
<th>IGW-discovery</th>
<th>IGW-selection-metrics</th>
<th>IGW-forwarding</th>
<th>Addressing</th>
<th>Handoff-style</th>
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<tr>
<td>2</td>
<td>MIPMANET [73]a</td>
<td>Flooding RREQ Proactive</td>
<td>Shortest-hop-count</td>
<td>Half-tunneling &amp; AODV [12]a</td>
<td>Not specified, but Home Address must be IP-global unicast</td>
<td>Route-optimization-based</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>MIP+OLSR [173]a</td>
<td>Using routing table Proactive</td>
<td>Not specified, implicitly shortest-hop-count</td>
<td>Default route &amp; OLSR [18]a</td>
<td>Not specified</td>
<td>Forced (when a prefix change)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>MEWLANATD/RD [187]a</td>
<td>Using routing table (DSDV) or TBBR-Tree Proactive</td>
<td>Shortest-hop-count</td>
<td>Default route &amp; DSDV or TBBR</td>
<td>Not specified</td>
<td>Forced (when a route change or node leave)</td>
<td></td>
</tr>
</tbody>
</table>
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**

---

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]

A New Proposed Internet Gateway Selection Metric

\[
\text{Min}\{w(i, j)\} \quad j \in V_{IGW} \quad (1)
\]

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

\[
\alpha_1 + \alpha_2 + \alpha_3 = 1
\quad (3)
\]

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

\[
LB_{MANET}(i, j) = \begin{cases} 
0 & \text{if } \left[\text{AvgDeg}(i, j)\right] \mod K = 0 \\
\frac{1}{\left[\text{AvgDeg}(i, j)\right] \mod K}, & \text{otherwise}
\end{cases} \quad (5)
\]

\[
\text{AvgDeg}(i, j) = \begin{cases} 
\left(l_j.w_j - \frac{r.(l_j + w_j)}{2} + r^2\right) \left(l_j.w_j\right)^2, & \text{if } i: \text{local} \\
\left(l_j.w_j - \frac{r.(l_j + w_j)}{2} + r^2\right) \left(l_j.w_j\right)^2, & \text{if } i: \text{visited}
\end{cases} \quad (6)
\]

**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]
Simulation Results

TCP Delivery Ratio

Simulation Case Studies

CBR Delivery Ratio

Simulation Case Studies

Normalized Signaling Overhead

Simulation Case Studies


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


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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)

A gateway to outreach the world while studying in Vietnam
Arch-AdSenNets

Protocol Stack in Arch-AdSenNets

MANETs site
- Applications Middlewares
- Transport Layer
  - [Ad-Hoc Routing: Link-state based/Low latency]
    - Deliver sensor events to MANETs nodes
    - Deliver instructions/queries via gateways to sensors
    - Ad-hoc communications for supporting decision
  - [MAC+PHY]
    - IEEE 802.11 DCF

Interworking Function (IWF)

SensorNets site
- Application-specific User Tasks and Queries Middlewares
- [Transport Layer]
  - Reliable delivering events to actors/sinks
  - Global/Wide-area collaborative information processing
- In-Network Data Aggregation
  - Data Dissemination/Diffusion
  - Distributed Data-Storage at Concentrators/Gateways
- [SensorNets Routing: Energy-efficient/Low delay/Scalable]
  - Deliver events from sensors to gateways
  - Deliver instructions/queries from gateways to sensors
  - Geographic-based forwarding
- [MAC+PHY]
  - Reliable event detections via local collaboration
  - Energy-efficiency
    - IEEE 802.15.4
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 $T = \sqrt{N_A} \cdot \tau$
  - Action types of MANET nodes
    - Processing
    - Movement
    - Resource consumption rate is the same: $[\varphi/sec]$
  - 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:
\[ V_M, V_A, V_S, V_{M/A}, \dot E^i, \dot E_T, \gamma_T, C, C_m, \varphi, T, l, w, D, v \]  

Find:
\[ \forall A_j, A_n \in V_A, \forall m \in V_M, \forall e_m \in E^i : x_{jn/m}^i, y_{j}^{e_m}(i,m) \]  

Goal:
\[ \text{Max} \{ u^i \} = \text{Max} \left\{ \sum_{A_j \in V_A} \sum_{m \in V_{M/A}} \sum_{e_m \in E^i} y_{j}^{e_m}(i,m) \right\}, \text{Min} \{ c^i \} = \text{Min} \left\{ \sum_{A_j \in V_A} \sum_{n \in V_A} \sum_{m \in V_{M/A}} d_{jn} \tau \cdot x_{jn/m}^i \right\} \]

Subject to constraints:

\[ \forall A_j, A_n \in V_A, \forall m \in V_M : x_{jn/m}^i \in \{0,1\} \]  

\[ \forall m \in V_M, \forall A_j \in V_A : \sum_{A_n \in V_A} x_{jn/m}^i \in \{0,1\} \]  

\[ \forall A_j \in V_A, \forall m \in V_M, \forall e_m \in E^i : 0 \leq \varphi \cdot y_{j}^{e_m}(i,m) \leq C_m^i \]  

\[ \forall m \in V_M : \varphi \left( \sum_{e_m \in E^i} y_{j}^{e_m}(i,m) + \sum_{n \in V_A} d_{jn} \cdot \tau \cdot x_{jn/m}^i \right) \leq C_m^i \]  

\[ \forall A_j \in V_A, e_m \in E^i : \sum_{m \in V_{M/A}} y_{j}^{e_m}(i,m) \leq \tau_{j}^{e_m} \]
Network Model [Distributed Algorithms]

Actor/Data Concentrator ($A_j \in V_A$) MANETs Node ($m \in V_M$)

Triggered if both:
- periodically at the beginning of each observation cycle
- Need more MANETs nodes for processing

Advertising (ADV) Packet Content:
- No. of unprocessed/not-finished/new events ($E_{ij}$)
- Calculating No. of new MANETs nodes needed for processing
- Attaching its Location

Waiting time ($t_{ADV}^{WM}$), application-specific

Bid (BID) Packet Content:
- No. of hops (in actor coverage area) to all advertised actors that this node received ADVs

Waiting time ($t_{BID}^{WM}$), application-specific

Invitation (INV) Packet Content:
- No. of MANETs nodes in 1-hop, 2-hop,...need to move into this actor area for processing
- Determining by running SELECT algorithm
- Attaching its Location

Waiting time ($t_{INV}^{WM}$), application-specific

Confirm (FIX) Packet Content:
- Only the shortest number of hops (in average coverage area) to the nearest actor it will move into for processing

Optimized Problem
Centralized
Solved by Micro-GA [See ref.]

Developing Distributed Algorithm

Setup Phase: Initial Allocation of MANETs achieving 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 versa
      – 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

<table>
<thead>
<tr>
<th>Pareto Optimal Set of Case Study LA.T (10x10x2f, 100m/s, 300m, T=120; F=24f)</th>
<th>Processing Time (Utility) Comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pareto Index</td>
<td>f1</td>
</tr>
<tr>
<td>-------------</td>
<td>----</td>
</tr>
<tr>
<td>1</td>
<td>146,772</td>
</tr>
<tr>
<td>2</td>
<td>169,4420</td>
</tr>
<tr>
<td>3</td>
<td>114,9070</td>
</tr>
<tr>
<td>4</td>
<td>143,6000</td>
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<tr>
<td>5</td>
<td>149,8160</td>
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<tr>
<td>6</td>
<td>121,8210</td>
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<tr>
<td>7</td>
<td>132,3250</td>
</tr>
<tr>
<td>8</td>
<td>118,2970</td>
</tr>
<tr>
<td>9</td>
<td>136,7860</td>
</tr>
<tr>
<td>10</td>
<td>147,0840</td>
</tr>
</tbody>
</table>

\[
\max \{f_1(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, y_1, y_2, y_3, y_4, y_5, y_6, y_7, y_8)\}
\min \{f_2(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, y_1, y_2, y_3, y_4, y_5, y_6, y_7, y_8)\}
\]

\[
U = f_1(x_1, y_1 + x_8, y_3) + (x_4, y_4 + x_2, y_5 + x_7, y_7) + (x_1, y_2 + x_3, y_6 + x_6, y_8)
\]

\[
C = f_2 = \tau(x_1 + x_4 + x_2 + x_3 + x_5 + x_6)
\]

Constraints:
\[
x_{i(1 \leq i \leq 8)} \in \{0,1\}
\]

\[
0 \leq y_{i(1 \leq i \leq 8)} \leq 2.\tau
\]

\[
0 \leq (x_7, y_1 + x_1, y_2 + 2.\tau, x_1) \leq 2.\tau
\]

\[
0 \leq (x_8, y_3 + x_4, y_4 + 2.\tau, x_4) \leq 2.\tau
\]

\[
0 \leq (x_2, y_5 + 2.\tau, x_2 + x_3, y_6 + 2.\tau, x_3) \leq 2.\tau
\]

\[
0 \leq (x_5, y_7 + 2.\tau, x_5 + x_6, y_8 + 2.\tau, x_6) \leq 2.\tau
\]

\[
0 \leq (x_7, y_1 + x_4, y_4 + x_2, y_5 + x_5, y_7) \leq 4.\tau
\]

\[
0 \leq (x_1, y_2 + x_8, y_3 + x_3, y_6 + x_6, y_8) \leq 8.\tau
\]

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

### 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)

### 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)

### Table 1: First Simulation Scenario (4M x 4M x 2E, 300mx300m, E1=120 sec, E2=240 sec) A.1

<table>
<thead>
<tr>
<th>MANETs</th>
<th>t₀</th>
<th>t₁</th>
<th>t₀</th>
<th>t₁</th>
<th>t₀</th>
<th>t₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>A1</td>
<td>A2</td>
<td>_</td>
<td>_</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>M2</td>
<td>A1</td>
<td>A2</td>
<td>_</td>
<td>_</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>M3</td>
<td>A1</td>
<td>A2</td>
<td>_</td>
<td>A2</td>
<td>0.0000</td>
<td>14.1171</td>
</tr>
<tr>
<td>M4</td>
<td>A2</td>
<td>A2</td>
<td>_</td>
<td>_</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0000</td>
<td>14.1171</td>
</tr>
</tbody>
</table>

### Processing Time of all MANETs nodes [sec]

<table>
<thead>
<tr>
<th>ACTOR</th>
<th>t₀</th>
<th>t₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>120,000</td>
<td>0.0000</td>
</tr>
<tr>
<td>A2</td>
<td>55,000</td>
<td>185,000</td>
</tr>
<tr>
<td>A3</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>A4</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Total</td>
<td>175,000</td>
<td>185,000</td>
</tr>
<tr>
<td>Finish at</td>
<td>110,000</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2: First Simulation Scenario (4M x 4M x 2E, 300mx300m, E1=120 sec, E2=240 sec) A.2

<table>
<thead>
<tr>
<th>MANETs</th>
<th>t₀</th>
<th>t₁</th>
<th>t₀</th>
<th>t₁</th>
<th>t₀</th>
<th>t₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>A2</td>
<td>A1</td>
<td>_</td>
<td>_</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>M2</td>
<td>A2</td>
<td>A1</td>
<td>_</td>
<td>A1</td>
<td>0.0000</td>
<td>10.6614</td>
</tr>
<tr>
<td>M3</td>
<td>A2</td>
<td>A1</td>
<td>_</td>
<td>A1</td>
<td>0.0000</td>
<td>11.9008</td>
</tr>
<tr>
<td>M4</td>
<td>A2</td>
<td>A1</td>
<td>_</td>
<td>A1</td>
<td>0.0000</td>
<td>13.5201</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0000</td>
<td>36.0823</td>
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</tbody>
</table>

### Processing Time of all MANETs nodes [sec]

<table>
<thead>
<tr>
<th>ACTOR</th>
<th>t₀</th>
<th>t₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.0000</td>
<td>120,000</td>
</tr>
<tr>
<td>A2</td>
<td>240,000</td>
<td>0.0000</td>
</tr>
<tr>
<td>A3</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>A4</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Total</td>
<td>240,000</td>
<td>120,000</td>
</tr>
<tr>
<td>Finish at</td>
<td>105,000</td>
<td></td>
</tr>
</tbody>
</table>
Results Comparison

max \left\{ 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}) \right\}

min \left\{ 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}) \right\}

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|is\in\{12\}} \in \{0,1\}

0 \leq y_{i|is\in\{12\}} \leq 2\tau

0 \leq (x_7, y_1 + x_1, y_2 + \tau x_1) \leq 2\tau

0 \leq (x_8, y_3 + x_4, y_4 + \tau x_4) \leq 2\tau

0 \leq (x_2, y_5 + \tau x_2 + x_3, y_6 + \tau x_3) \leq 2\tau

0 \leq (x_9, y_7 + \tau x_5 + x_6, y_8 + \tau x_6) \leq 2\tau

0 \leq (x_9, y_9 + 2\tau x_9 + x_{10}, y_{10} + 2\tau x_{10}) \leq 2\tau

0 \leq (x_{11}, y_{11} + 2\tau x_{11} + x_{12}, y_{12} + 2\tau x_{12}) \leq 2\tau

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

0 \leq (x_1, y_2 + x_3, y_3 + x_6, y_6 + x_8, y_8 + x_{10}, y_{10} + x_{12}, y_{12}) \leq 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 (\tau/D/v=150/5=30 sec, observation cycle: T=2\tau=60 sec)

+ Event E1 in A1 (T1=8\tau=240 sec)

+ Event E2 in A2 (T2=8\tau=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)
Results Comparison

- utility values of simulation are always larger than those of $\max\{\max\{f_1\}\}$
- cost values of simulation are always lower than those of $\max\{\max\{f_1\}\}$
  - the simulation results converge to the theoretical optimal results (Pareto optimal set) solved by the Micro-GA.

<table>
<thead>
<tr>
<th>Values</th>
<th>Theoretical optimal values solved by the Micro-GA</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\max{\max{f_1}}$ case</td>
<td>$\min{\min{f_2}}$ case</td>
</tr>
<tr>
<td>Case study I.A.1</td>
<td>168,4420</td>
<td>39,7239</td>
</tr>
<tr>
<td>Case study I.A.2</td>
<td>168,4420</td>
<td>39,7239</td>
</tr>
<tr>
<td>Case study I.B</td>
<td>188,7400</td>
<td>44,3693</td>
</tr>
<tr>
<td>Case study II</td>
<td>219,2940</td>
<td>155,6000</td>
</tr>
</tbody>
</table>

Contacts

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