A Framework for Integrated Routing, Scheduling and Traffic Management in Ad Hoc Networks

**STORM**: Scheduling and Traffic Management in Ordered Routing Meshes

Rolando Menchaca-Méndez

Laboratorio de Comunicaciones y Redes de Computadoras
Motivation

- In protocol-stack architectures, protocols are decoupled from the physical medium and each protocol operates independently of others.
  - This has worked well in wired networks.
- However, the same approach is not well suited for wireless ad hoc networks, where:
  - links suffer from multiple access interference (MAI),
  - bandwidth is relatively scarce, and
  - topologies change because of node mobility and physical-layer effects (e.g., fading and noise).
Motivation

- The stark differences between wireless and wired networks call for a cross-layer approach to managing network resources in support of information dissemination
  - Real-time or elastic traffic
  - Unicast or multicast data flows
STORM: Scheduling and Traffic Management in Ordered Routing Meshes

- Priority-based queuing system
- Interest-Driven routing algorithm
  - Unicast
  - Multicast
- Distributed transmission scheduling algorithm
  - Reservations
  - Elections based on node identifiers
- Reservation algorithm that integrates scheduling and routing decisions to guarantee end-to-end delays for real-time traffic
- A neighbor protocol
STORM: Architecture

Integrated Unicast/Multicast Routing and Scheduling

Neighbor Protocol
Reservation Protocol

Queue Manager

IP Queues

Phy
STORM: MAC Frame

Frames composed of $N$ slots

Slot 0 **Reserved** by node $k$

Special slot used by new nodes to join the network

$t$: 0 1 2 $\ldots$ $kN$

$0 1 2 N 2N kN$

_Won_ by $h$ using a **per slot** hash-based election

_Owned_ by $u$ using a **per frame** hash-based assignation

N-1
Algorithm 1: ChannelAccess\( (N(N(u), u) \) 

1. \( \text{if } (t + id^u) \mod N = 0 \text{ then} \)
   
2. \( C \leftarrow \{v : v \in N(N(u)) \land (t + id^v) \mod N = 0\}; \)
   
3. \( \text{if } C = \emptyset \text{ then} \)
   
4. \( \text{Access channel;} \)
   
5. \( \text{else} \)
   
6. \( \text{compute } p^t_u = \text{Hash}(id^u \oplus t) \oplus id^u; \)
   
7. \( \forall v \in C \text{ compute } p^t_v = \text{Hash}(id^v \oplus t) \oplus id^v; \)
   
8. \( \text{if } \forall v \in C : p^t_u > p^t_v \text{ then} \)
   
9. \( \quad \text{Access channel;} \)
   
10. \( \text{else} \)
   
11. \( \quad \text{Listen to channel;} \)
   
12. \( \text{else} \)
STORM: Channel Access Algorithm

if $\exists v \in N(N(u)) \mid (t + id^v) \mod N = 0$ then
    Listen to channel;
else
    if $u$ has reservation on $t \mod N$ then
        Access channel;
    else
        if $\exists v \in N(N(u)) \mid v$ has reservation on $t \mod N$ then
            Listen to channel;
        else
            for $v \in N(N(u)) \cup \{u\}$ do
                compute $p^t_v = \text{Hash}(id^v \oplus t) \oplus id^v$;
            if $\forall v \in N(N(u)) \mid p^t_u > p^t_v$ then
                Access channel;
            else
                Listen to channel;
        end for
    end if
end if
endif
endif
STORM: MAC Frame

Frames composed of N slots

Slot 0 Reserved by node k

Special slot used by new nodes to join the network

Won by h using a hash-based election

Owned by u using a hash-based assignation

Frames of N slots:

0 1 2

Reservation Packet  Control Packet  Hello Packet

Reservation Packet  Data Packet
STORM: Queueing System

- All queues are FIFO and are served using a priority-based algorithm

\[ \rho_{\text{Hello}}^- < \rho_{\text{elastic}} < \rho_{\text{RT}} < \rho_{\text{RT}^+} < \rho_{\text{ctr}} < \rho_{\text{Hello}^+} < \rho_{\text{Rsv}} \]

- If more than one nonempty queue with the highest priority exist, these queues are served on a round-robin fashion

- The priority of RT queues is dynamic
  - It is increased if the current slot was reserved on behalf of that particular flow
STORM: Queueing System

Queue Manager: node $i$

- Ctr
- Elastic
- RT queues: $f_1$, $f_2$, ..., $f_n$
- Neighbor
- Reserv

Slot Won by $i$: 
STORM: Queueing System

Queue Manager: node $i$

Slot Won by $i$: Reservation Packet, Control Packet, Hello Packet
STORM: Queueing System

Queue Manager: node $i$

Slot Reserved by $i$ for flow $f_2$: 
STORM: Queueing System

Queue Manager: node $i$

Slot Reserved by $i$ for flow $f_2$:

At this particular slot, Flow $f_2$ has higher priority than the other flows.
STORM: Integrated Routing and Scheduling
STORM: Integrated Routing and Scheduling

The first source disseminates a Mesh Request (\textit{MR})
Using Mesh Announcements (MA): A core for the destination is elected and a partial ordering is established
STORM: Integrated Routing and Scheduling

It also establishes a region of interest

STORM establishes a routing mesh composed of shortest paths between sources and destination
Am I flow ordered?

Am I flow ordered?

Am I flow ordered?

Am I flow ordered?

Am I flow ordered?

Am I flow ordered?

Am I flow ordered?
Flow Ordered Reservations

\[ d^x_D = 2 \quad \Delta \quad d^x_D = 1 \]

Do I have available slots in the interval:

\[ (slot_D - d^x_D \Delta) \mod N, ((slot_D - d^x_D \Delta) \mod N + \Delta) \mod N \]
Flow Ordered Reservations

FIRST:

Non-coordinated reservations:

\[ d^x_D = 3 \quad d^x_D = 2 \quad d^x_D = 1 \]
STORM: Integrated Routing and Scheduling
STORM: Integrated Routing and Scheduling

STORM establishes a flow ordered routing mesh composed of nodes with available slot in the adequate positions.
Destinations are connected components of the network.
STORM: Integrated Routing and Scheduling

Slot \((\rho - 6\Delta) \text{mod} N\) reserved by node \(S\):

Frames of \(N\) slots

\(S\):

Frames of \(N\) slots
STORM: Integrated Routing and Scheduling

Slot \((\rho - 6\Delta) \mod N\) reserved by node S

Frames of N slots

Slot \((\rho - 5\Delta) \mod N\) reserved by p₁

p₁:

S:

Slot \((\rho - 6\Delta) \mod N\) reserved by node S

Frames of N slots

fₜ

p₁
STORM: Integrated Routing and Scheduling

Frames of N slots

Slot (ρ-6Δ) mod N reserved by node S

Slot (ρ-5Δ) mod N reserved by p1

Slot (ρ-3Δ) mod N reserved by R2

S:

R2:

p1:

...Slot (ρ-3Δ) mod N reserved by R2
R2:

Slot (ρ-5Δ) mod N reserved by p1
p1:

Slot (ρ-6Δ) mod N reserved by node S
S:

Frames of N slots

...Slot (ρ-3Δ) mod N reserved by R2
R2:

Slot (ρ-5Δ) mod N reserved by p1
p1:

Slot (ρ-6Δ) mod N reserved by node S
S:

Frames of N slots
Correctness

- **Theorems 1 and 2.** Data packets are routed from sources to destinations along *loop-free paths*
  - Meshes are ordered using destination sequence numbers and distances to the destination
  - Local repair operations preserve this ordering
Theorem 3. The maximum end-to-end delay experienced by a real-time data packet that fits in a time slot and is transmitted from $n_1$ to $n_D$ is $\Delta l$. 

- End-to-End reservations
  - Maximum delay between relays is bounded
- Queueing system eliminate interference among flows that traverse one or more common nodes
  - Real-time flows have priority over their reserved slots
- Loop-free paths
Correctness

- **Theorem 4** The maximum end-to-end delay experienced by a **multicast real-time data packet** that fits in a time slot and is transmitted from \( n_1 \) to the multicast group \( D \) is \( \Delta T(l + m) \) seconds.
  - \( l \) is the length of a successor path connecting the source \( n_1 \) with the core
  - \( m \) is the length of the longest successor path connecting any multicast receiver to the core.
Performance Results

- We present simulation results comparing **STORM** against **ODMRP** for the case of multicast traffic, as well as against **AODV** with **ODMRP** and **OLSR** with **ODMRP** for the case of combined unicast and multicast traffic.

- Performance metrics:
  - Packet delivery ratio
  - Generalized group delivery ratio (multicast)
  - End-to-end delay
  - Total overhead
Simulation Environment

- Qualnet 3.9
  - 100 nodes in a simulation area of $1800 \times 1800 \text{m}^2$
  - Combination of Group and Random Waypoint mobility models
    - 1-20m/s and pause time of 10s – R.W.
    - 1-20m/s and pause time of 10s – Group mobility
  - 802.11b at 11000000bps
  - MCBR and CBR
    - 1000 pkts per source, 10 packets per second
Multicast: Increasing Number of Flows – Delivery Ratio
Multicast: Increasing Number of Flows – Group Delivery Ratio
Multicast: Increasing Number of Flows – E2E Delay

![Graph showing the relationship between the number of concurrent senders and average end-to-end delay for different multicast protocols.]
Multicast: Increasing Number of Flows – Overhead

Number of Concurrent Senders

Average Total Number of Packets Transmitted per Node

- STORM
- ODMRP
- RWP: STORM
- RWP: ODMRP

![Graph showing the relationship between the number of concurrent senders and the average total number of packets transmitted per node for different multicast protocols.](image-url)
Combined Traffic: Increasing Number of Groups and Flows: Delivery Ratio
Combined Traffic: Increasing Number of Groups and Flows: Group DR

- Number of Concurrent Active Groups
- Group Delivery Ratio (80%)
  - STORM RT+elastic
  - STORM RT
  - STORM elastic
  - ODMRP+AODV
  - ODMRP+OLSR

Graph showing the relationship between the number of concurrent active groups and the group delivery ratio for different protocols.
Combined Traffic: Increasing Number of Groups and Flows: E2E Delay

![Graph showing average end-to-end delay vs. number of concurrent active groups for different protocols.]

- STORM RT+elastic mcast
- STORM RT mcast
- STORM elastic mcast
- STORM RT ucast
- ODMRP with AODV
- AODV with ODMRP
- ODMRP with OLSR
- OLSR with ODMRP
Combined Traffic: Increasing Number of Groups and Flows: Overhead

![Graph showing average total number of packets transmitted per node vs number of concurrent active groups. The graph compares STORM, ODMRP with AODV, and ODMRP with OLSR.]
Conclusions

- The main contribution of this work is to introduce and verify a new cross-layer framework for the dissemination of unicast and multicast flows that may be real-time or elastic.
- We proved that the routing meshes established with STORM are loop-free at any time and that the end-to-end reservations established along routing meshes provide bounded delays to real-time data packets.
Conclusions

- Simulation results show that STORM is very scalable and robust for both unicast and multicast traffic.
  - The end-to-end delays attained with STORM for unicast and multicast traffic comply with the ITU-T recommendation G.114
This work was sponsored in part by the U.S. Army Research Office (ARO) by the UC MEXUS-CONACyT program and by the Mexican National Polytechnic Institute (IPN).

Questions?