Token-Based Adaptive MAC for Two-Hop Device-to-Device Communications

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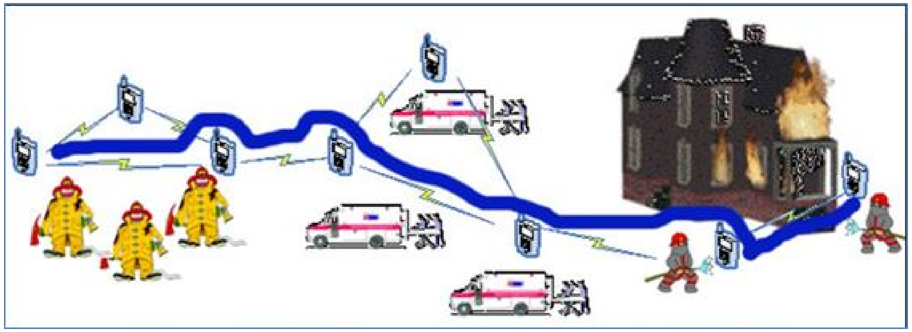
Device-to-Device (D2D) Communications

- **Definition**
  - Self-organized nodes interconnected for communications in a distributed manner
    - Low cost and simplified implementation
  - Ad hoc networking
    - Smart wireless devices (strong computing and smart sensing capabilities)

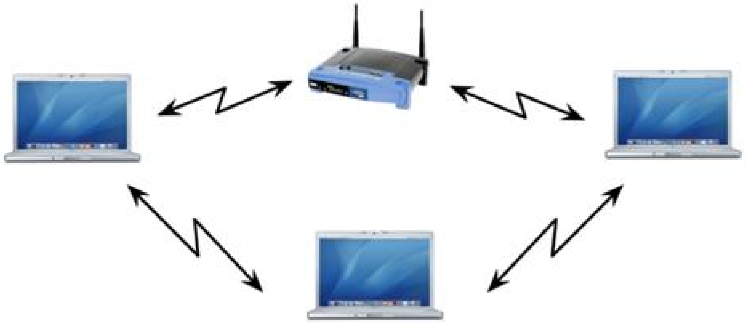
- **Characteristics**
  - Infrastructure-less
  - Node movement
  - Multi-hop communications
  - Increasing node number



- **Applications**
  - Emergency communications for disaster recovery
  - Smarting sensing for flood monitoring

Medium Access Control

- **Medium access control (MAC)**
  - Coordinate nodes’ channel access



- **Objective**
  - Low end-to-end packet transmission delay

- **Challenges for MAC in D2D communications**
  - Distributed network operation
    - Distributed MAC
  - Varying number of users
    - Traffic-adaptive MAC
  - Enlarged network region with an increasing number of users
    - Interference-aware and scalable MAC

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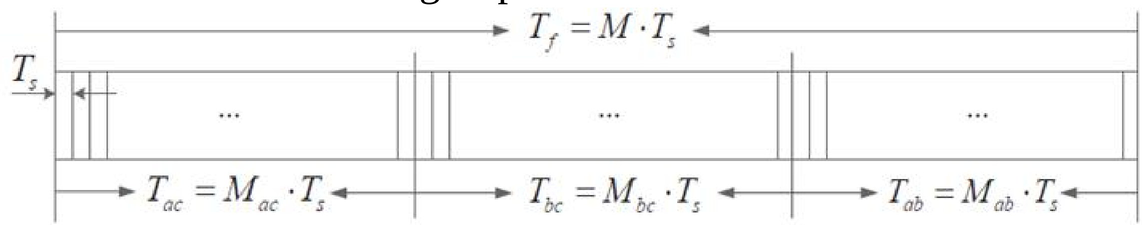
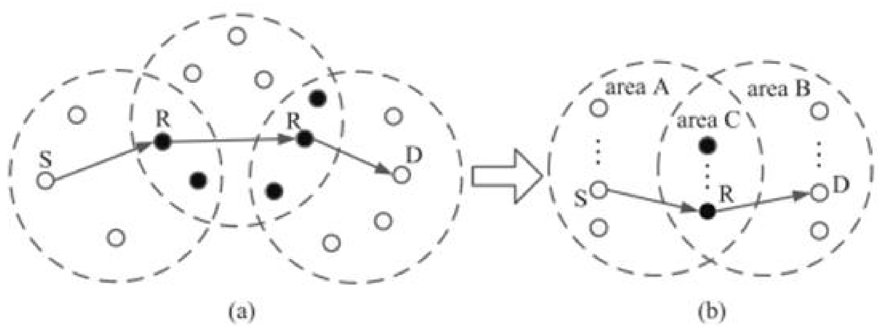
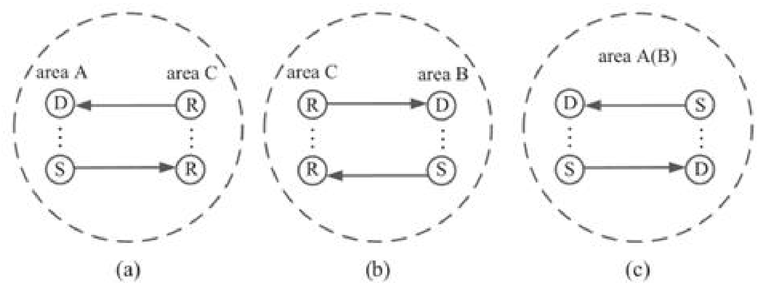
System Model

- A two-hop network with an error free channel
- N_a, N_b, N_c in areas A, B and C
- Sensing data traffic
- MAC superframe structure
  - Spatial reservation of time slots for different node groups
- Four one-hop subnetworks





(a) A general multi-hop MANET. (b) A simplified two-hop network.



Packet transmissions for four one-hop subnetworks during (a) T_{ac}. (b) T_{bc}. (c) T_{ab}.

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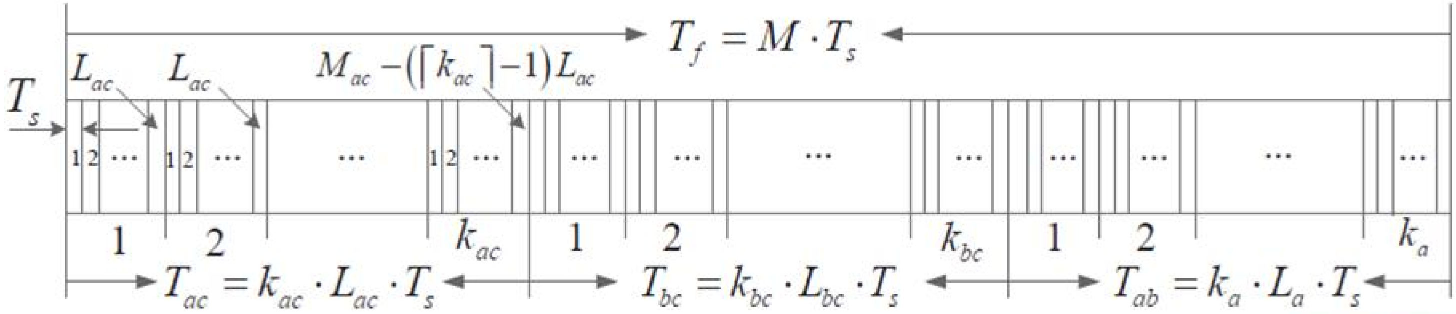
Token-based Adaptive MAC

- **Probabilistic token passing scheme**
  - Four token rings R_{ac}, R_{bc} and R_a (R_b) formed among each subnetwork
  - Tokens circulated probabilistically within each node group
    - One complete token rotation cycle
  - Numbers of token rotation cycles k_{ac}, k_{bc} and k_a (k_b) in durations T_{ac}, T_{bc} and T_{ab}
- **Important MAC parameters**
  - Number of token rotation cycles k_j for each node group
  - Total number of time slots M



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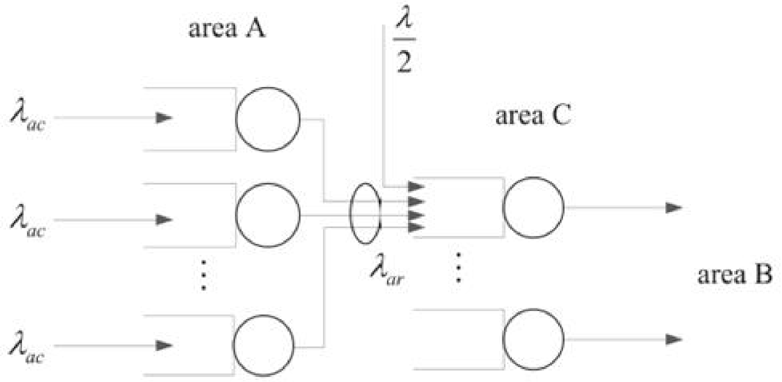
Performance Analysis

- **Compound packet arrival rate**
  - Poisson traffic approximation on each relay node (an extension to Kleinrock independence approximation)



- **Average end-to-end delay**

$$D_{ab} = \sum_{(n,j)\in\{(ac,ac),(cb,bc)\}} \left(\frac{\varepsilon_j}{k_j} + \frac{\lambda_n[\alpha_j k_j^2 + \beta_j k_j + \gamma_j]}{2(k_j - \lambda_n \varepsilon_j)} \right) \quad D_{ba} = \sum_{(n,j)\in\{(bc,bc),(ca,ac)\}} \left(\frac{\varepsilon_j}{k_j} + \frac{\lambda_n[\alpha_j k_j^2 + \beta_j k_j + \gamma_j]}{2(k_j - \lambda_n \varepsilon_j)} \right)$$

where $\alpha_j = L_j^2;\ \beta_j = -\frac{5L_j^2+12ML_j+1}{6};\ \gamma_j = M^2 + 2ML_j;\ \varepsilon_j = M$

- **Average delay for local transmissions in areas A and B**

$$D_j = \frac{\varepsilon_j}{k_j} + \frac{\lambda_j[\alpha_j k_j^2 + \beta_j k_j + \gamma_j]}{2(k_j - \lambda_j \varepsilon_j)} \quad (j = a, b)$$

where $\alpha_j = L_j^2;\ \beta_j = -\frac{5L_j^2+12ML_j+1}{6};\ \gamma_j = M^2 + 2ML_j;\ \varepsilon_j = M$

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Optimal MAC Parameters

- **Average end-to-end delay minimization with a given M**

$$(\mathbf{P1}): \min_{\mathbf{k}=[k_{ac},k_{bc},k_a,k_b]} \{\max\{D_{ab}(k_{ac},k_{bc}), D_{ba}(k_{ac},k_{bc})\}\}$$

$$\text{s.t.} \begin{cases} k_{ac}L_{ac} + k_{bc}L_{bc} + k_a L_a = M \\ k_a L_a = k_b L_b \\ \rho_n = \dfrac{\lambda_n}{\mu_j} < 1 \quad (n,j) \in \{(ca,ac),(cb,bc)\} \\ \rho_j = \dfrac{\lambda_j}{\mu_j} < 1 \quad (j = a,b) \\ D_j(k_j) \leq D_{th} \quad (j = a,b) \\ k_j \geq 1 \quad (j = ac,bc,a,b). \end{cases}$$

Solution: Problem decoupling

$$(\mathbf{SP1}): \min_{\mathbf{k_1}=[k_a,k_b]} k_a L_a$$

$$\text{s.t.} \begin{cases} k_a L_a = k_b L_b \\ \rho_j < 1 \quad (j = a,b) \\ D_j(k_j) \leq D_{th} \quad (j = a,b) \\ k_j \geq 1 \quad (j = a,b). \end{cases}$$

A convex subproblem

$$(\mathbf{SP2}): \min_{\mathbf{k_2}=[k_{ac},k_{bc}]} \{\max\{D_{ab}(k_{ac},k_{bc}), D_{ba}(k_{ac},k_{bc})\}\}$$

$$\text{s.t.} \begin{cases} k_{ac}L_{ac} + k_{bc}L_{bc} = M^* \\ \rho_n < 1 \quad (n = ca, cb) \\ k_j \geq 1 \quad (j = ac, bc) \end{cases}$$

where $M^* = M - k_a^* L_a$

A biconvex subproblem

$$\mathbf{k}^* = [k_{ac}^*, k_{bc}^*, k_a^*, k_b^*].$$

- **Calculate optimal total number of time slots**
  - Optimal parameter set $[k_j^{opt}, M^{opt}]$

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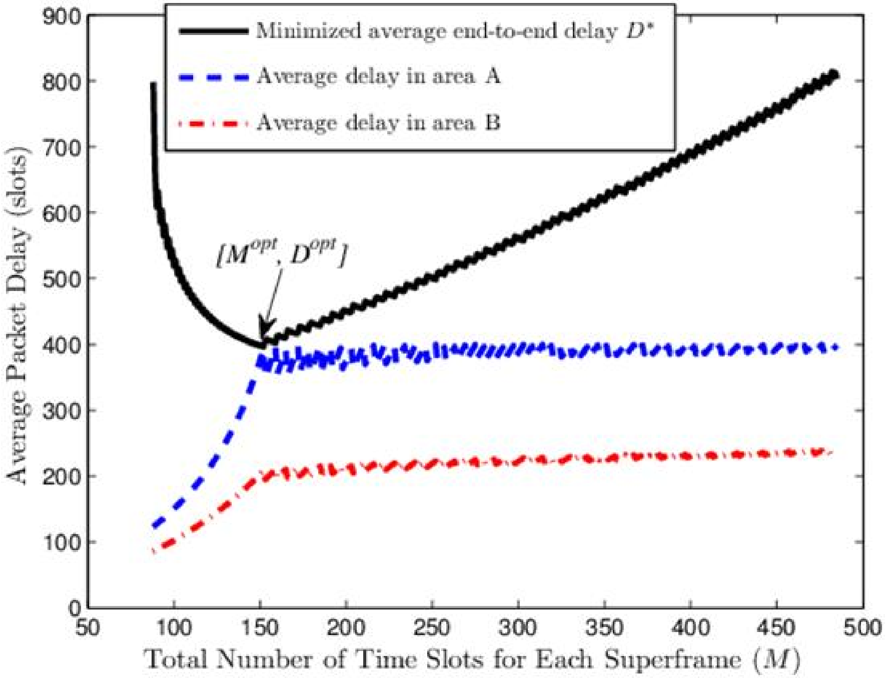
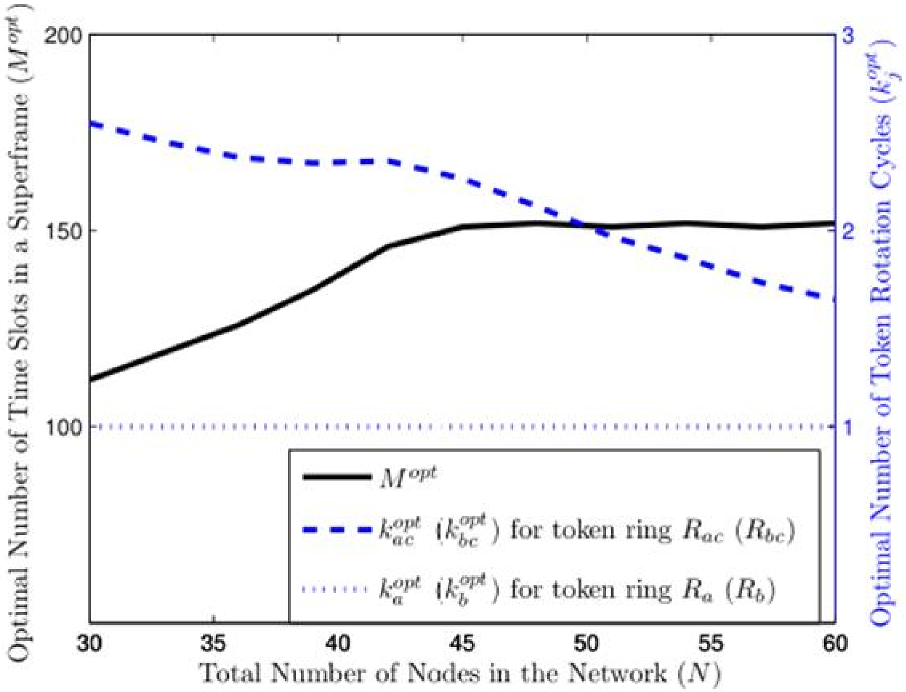
Numerical Results (1)

- **Optimal MAC parameters**
  - Optimal total number of time slots M^{opt} (slot duration: 1ms)
  - Optimal number of token rotation cycles k_j^{opt}



$N_a = 20,\ N_b = 15,\ N_c = 15$



$N_a = N_b = N_c$

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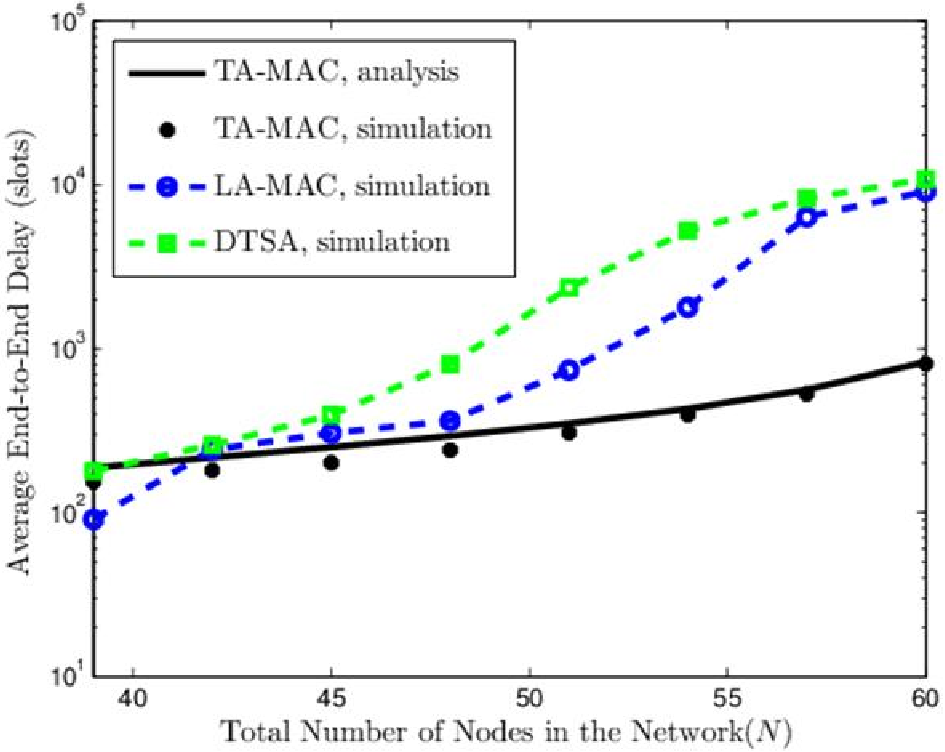
Numerical Results (2)

- **Performance comparison**
  - Load adaptive MAC (LA-MAC) and Dynamic time slot allocation (DTSA)



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Conclusions

- **A scalable token-based adaptive MAC for a two-hop network**
  - A TDMA-based superframe structure for spatial reservation of time resources among different groups of nodes
  - Probabilistic token passing for distributed time slot allocation
  - Closed-form performance analytical modeling for average end-to-end packet transmission delay in terms of MAC parameters (i.e., numbers of token rotation cycles and the superframe length)
  - Determine optimal MAC parameters to achieve minimal average end-to-end delay

Future Plan

- Specifically, we will investigate
  - how to form multiple concurrent device-to-device groups that share devices of richer power as cluster heads;
  - how to incorporate various types of data transmission to CAFFEWS data server and enhance transmission reliability;
  - how to improve initial source selection for data dissemination via device-to-device communications;
  - how to take advantage of user-provided information to expand the scope of data dissemination; and
  - to collaborate with other researchers in Theme 3 to refine/validate/test CAFFEWS.

Thank you!

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