SWINBURNE UNIVERSITY OF TECHNOLOGY

Reliable Transport in Delay Tolerant Networks

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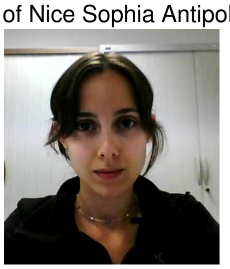


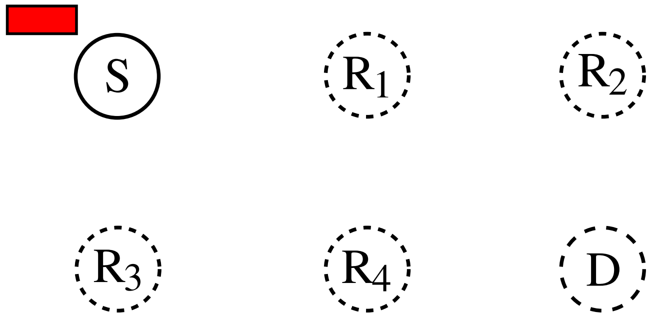
Tijani Chahed
(Telecom SudParis)

Eitan Altman
(INRIA Sophia Antipolis)

[1]
A. Ali, E. Altman, T. Chahed, M. Panda, L. Sassatelli, “A new reliable transport scheme in Delay Tolerant Networks based on acknowledgments and random linear coding,” *23rd International Teletraffic Congress (ITC)*, pp. 214–221, 2011.

Delay Tolerant Networks (DTNs)

- Sparse network with mostly isolated nodes
- Mostly disconnected - No contemporaneous end-to-end path exists at any time
- Nodes communicate when they come within the radio range
- Requires store-carry-and-forward method of routing



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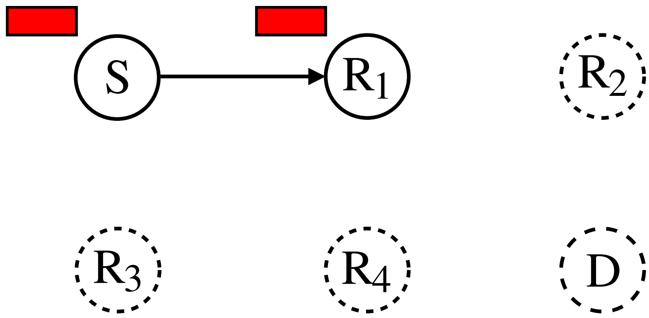

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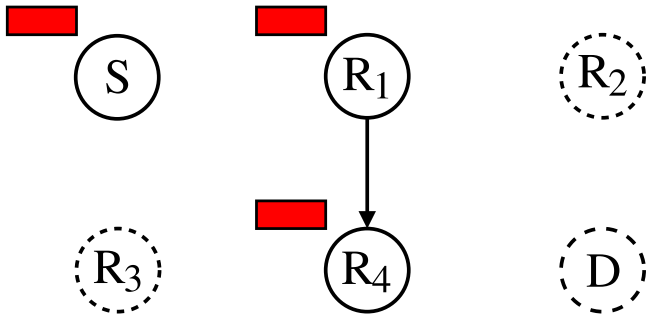

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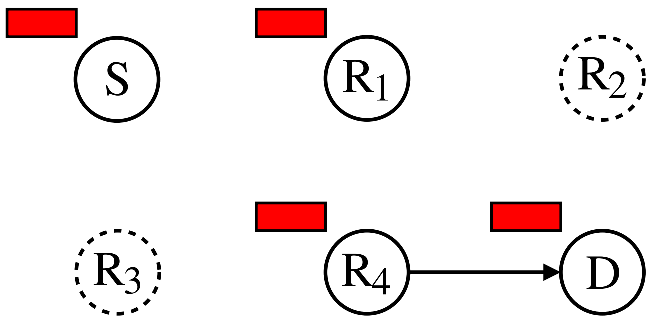

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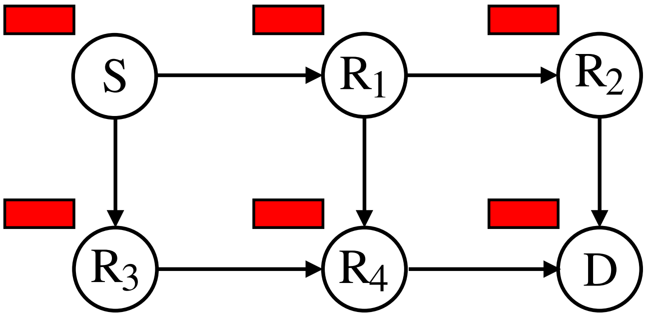

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Examples of DTNs

- Inter-planetary networks (IPNs)
- Sparse mobile ad hoc networks (MANETs)
- Sparse vehicular ad hoc networks (VANETs)
- Pocket switched networks (MSNs)
- Underwater networks (UWNs)
- Military battlefield networks
- Sensor networks for wildlife tracking
- Remote rural area (village) networks

Our Objective

Design a reliable transport mechanism for DTNs to minimize the end-to-end delivery delay

Literature on Reliable Transport in DTNs

- **Deep-Space**
  - TP-Planet, Bundle Protocol, SCPS-TP, CFDP, LTP, DS-TP, Saratoga, DTTP, ...
- **Terrestrial**
  - PCMP, HIP+TCP timeout and retransmission, ...
- The general approach is to modify TCP
  - Hop-by-hop reliability
  - Selective Negative ACKnowledgments (SNACKs)
  - Host identity and/or connectivity management

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  - Develop a fluid-limit analytical model
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- The framework
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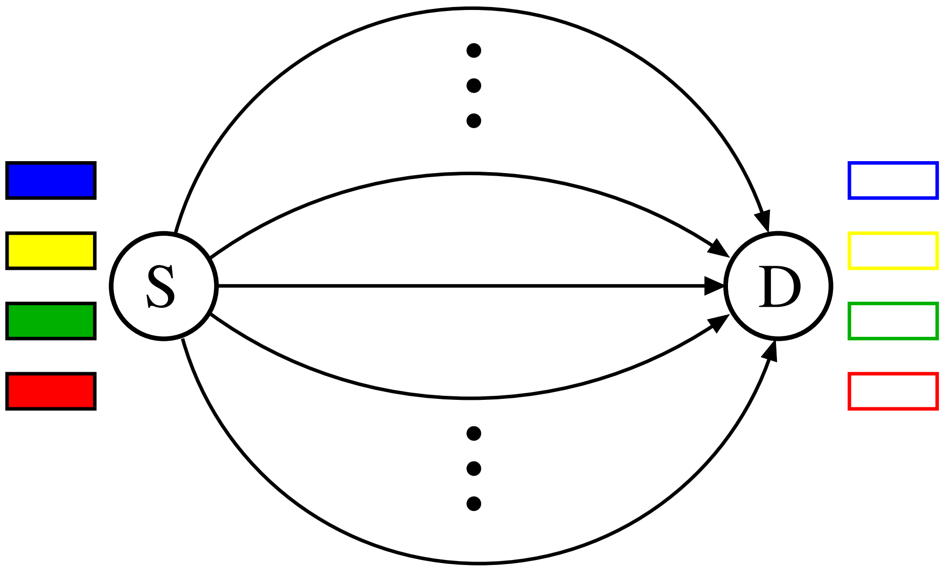
  - Optimize the parameters based on the analytical model
- Our transport mechanism is similar to Sundararajan et al [2]
  - Random Linear Coding at the source
  - Degree of Freedom (DoF) Acknowledgments (ACKs)

[2] J.K. Sundararajan, D. Shah, M. Medard, S. Jacubczak, M. Mitzenmacher, J. Barros, "Network Coding Meets TCP: Theory and Implementation," *Proceedings of the IEEE*, Vol. 99, No. 3, March 2011.

Transport With and Without Coding

TRANSPORT WITHOUT CODING



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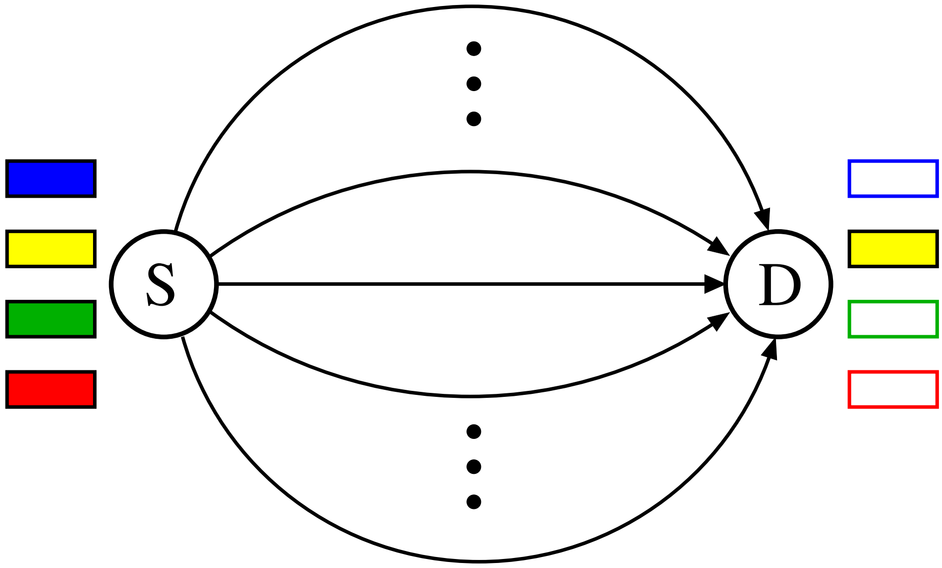

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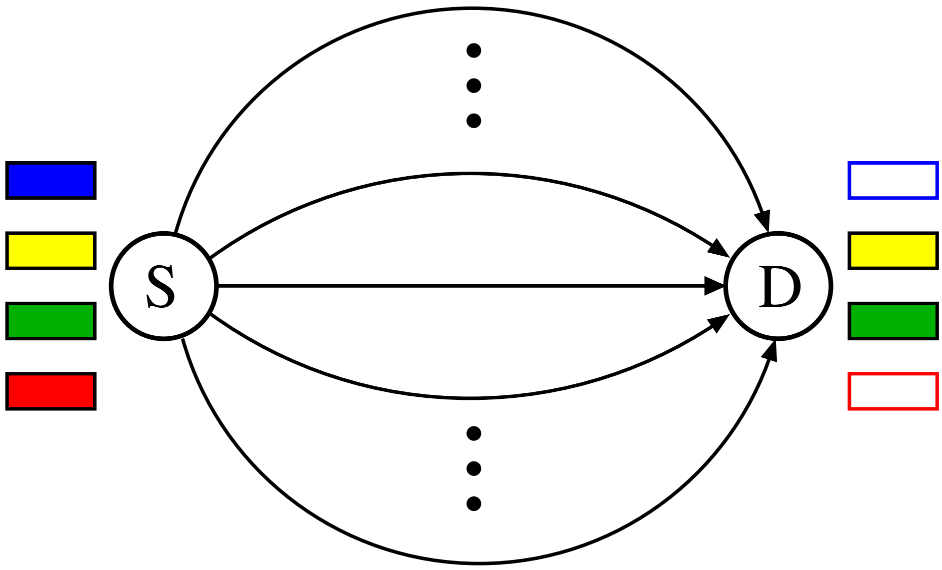

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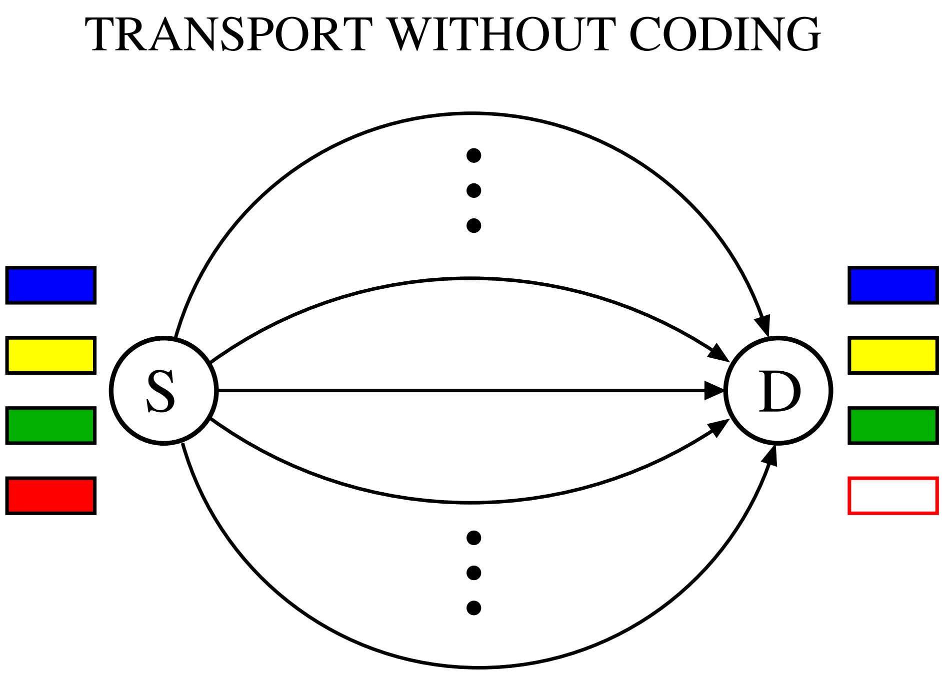

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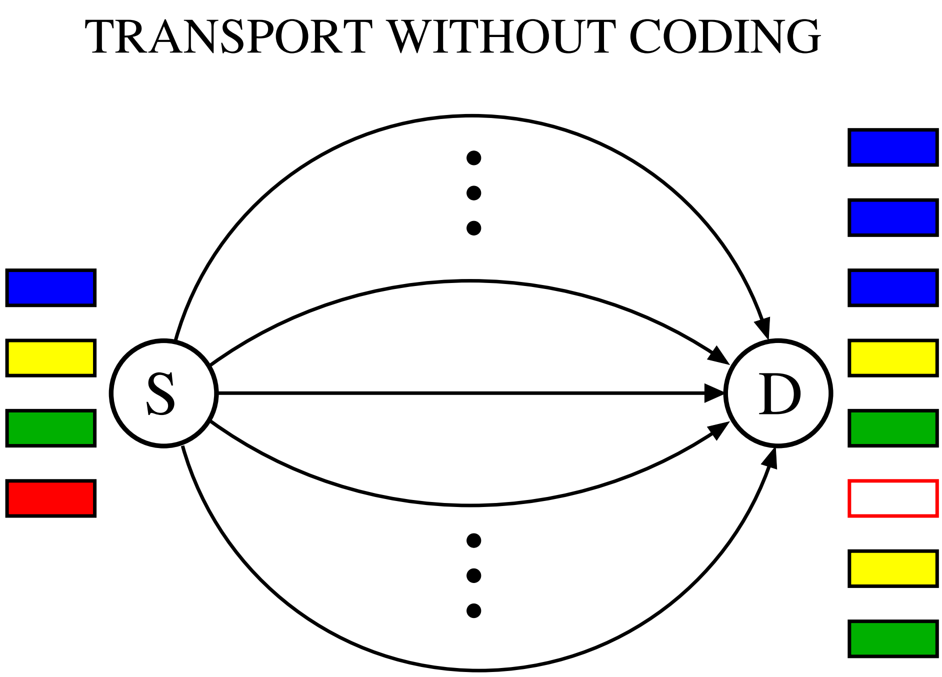

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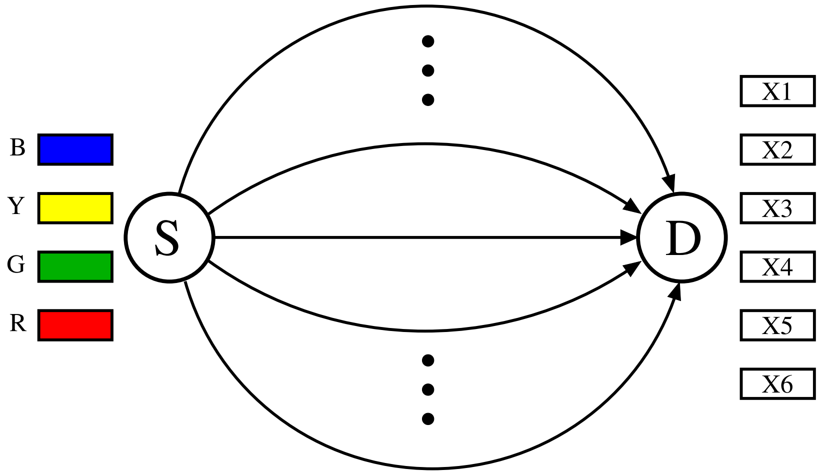

X1 = a1 B + b1 Y + c1 G + d1 R X2 = a2 B + b2 Y + c2 G + d2 R
X3 = a3 B + b3 Y + c3 G + d3 R X4 = a4 B + b4 Y + c4 G + d4 R
X5 = a5 B + b5 Y + c5 G + d5 R X6 = a6 B + b6 Y + c6 G + d6 R

Degrees of Freedom (DoF)

Destination receives $\mathbf{x} = [X1 \quad X2 \quad X3 \quad X4 \quad \ldots]^T$

Coding Vector for $X1$ is $[a1 \quad b1 \quad c1 \quad d1]$

$$\text{Decoding Matrix } \mathbf{D} = \begin{bmatrix} a1 & b1 & c1 & d1 \\ a2 & b2 & c2 & d2 \\ a3 & b3 & c3 & d3 \\ a4 & b4 & c4 & d4 \\ \vdots & \vdots & \vdots & \vdots \end{bmatrix}$$

D and **x** grow with time

Coded packets satisfy $\boxed{\mathbf{x} = \mathbf{D}\mathbf{y}}$ where $\mathbf{y} = [B \quad Y \quad G \quad R]^T$

Unique solution to **y** when **D** attains full rank

The source needs to receive as many Degrees of Freedom (DoF) as the number of original packets

Missing DoF = Number of native/original packets − Rank of **D**

ACKs carry the missing DoF at the destination

Outline

Our Proposed Transport Framework

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  - $M =$ Number of native/original packets to be sent
- **Assumptions**
  - A relay stores at most one data packet or ACK
  - Drops packets from buffer after an **expiry timeout**

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- **Source-Relay Meetings**
  - The source generates a Random Linear Combination (RLC)
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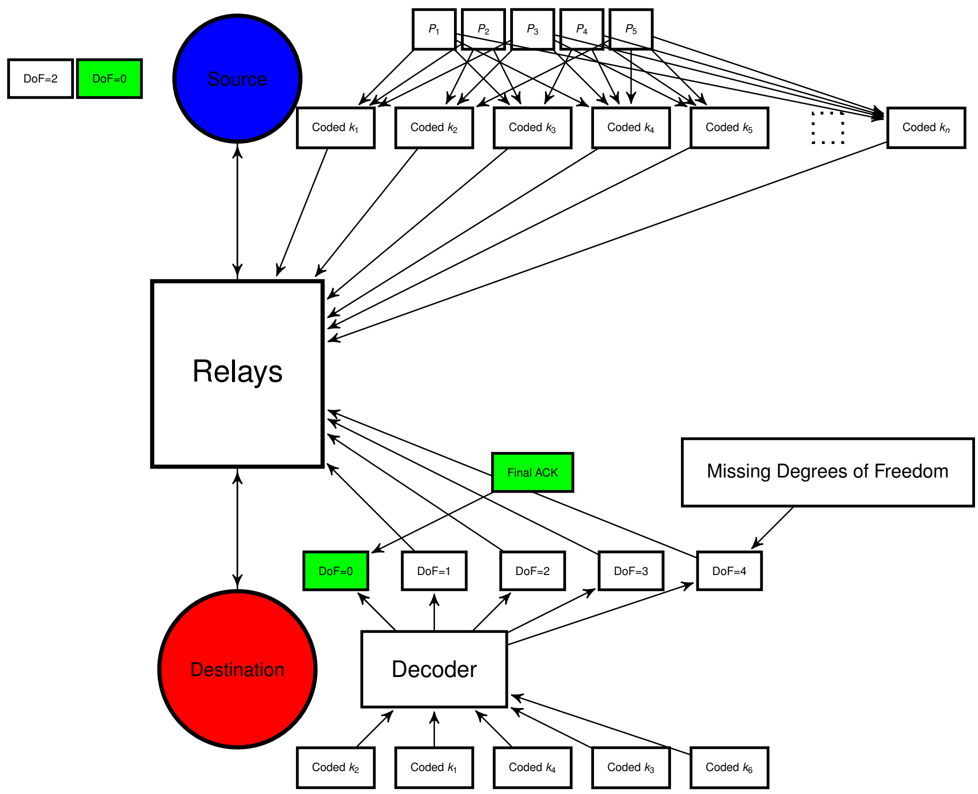
Network Operation with Coded Packets



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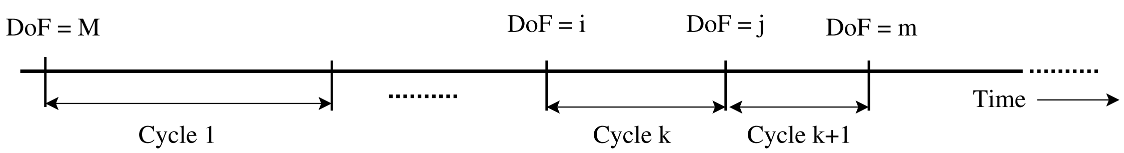
  - Limit the duration of waiting for ACKs - **ACK Waiting Time**
  - Drop everything after some time and restart - **Cycle Time**

Our Proposal Operates in Cycles



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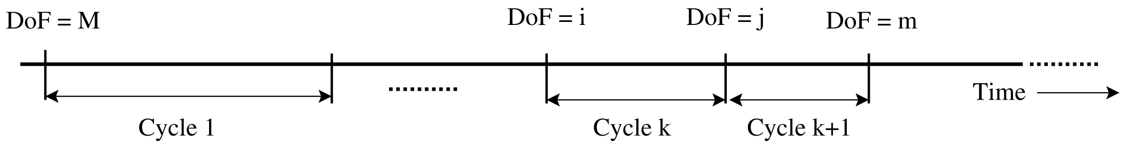

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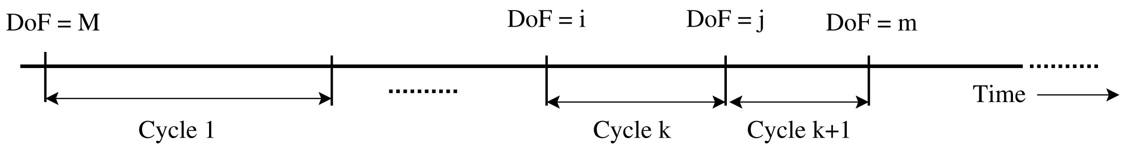

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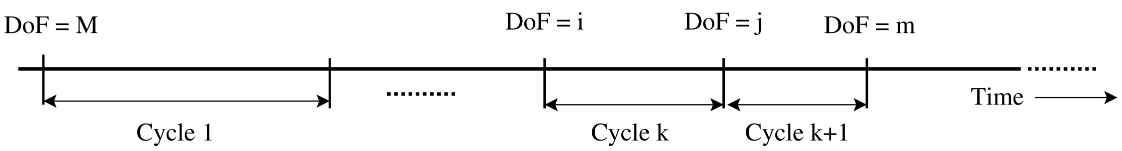

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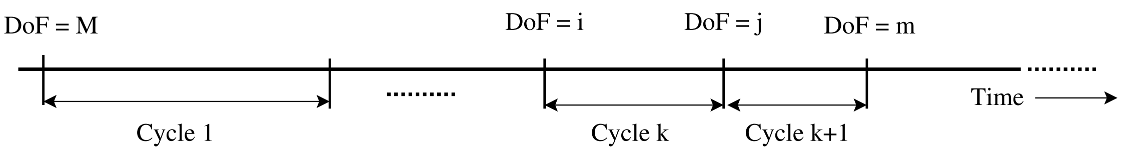

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- Continue until the source receives the final ACK

Structure of a Cycle

Suppose that the cycle begins with missing DoF i

- Control Parameters
  - M_i = Number of coded packets to be sent
  - $\tau_{i,S}$ = Spreading time
  - $\tau_{i,W}$ = ACK wait time
- t_k = Time of generation of coded packet k, $1 \leq k \leq M_i$
- Each coded packet is replicated for a duration $\tau_{i,S}$
- E.g., the coded packet k is replicated during $(t_k, t_k + \tau_{i,S}]$
- Cycle duration:

$$\tau_i := t_{M_i} + \tau_{i,S} + \tau_{i,W}$$

- There can be up to $i - 1$ ACKs indicating missing DoF = $i - 1, \ldots, 0$

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- Exponentially distributed buffer expiry time
  - $\tau_e = 1/\beta_e =$ Mean time to buffer expiry

Fluid-Limit Equations

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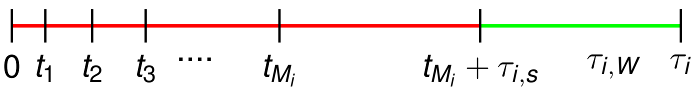
Coded packets replication

- $x_k(t)$ = fraction of relay nodes having the coded packet k
- $y_l(t)$ = fraction of relay nodes having the ACK l
- $x(t) := \sum_k x_k(t)$, $y(t) := \sum_k y_k(t)$
- $q_k(t)$ = Pr($k - 1$ source-relay meetings up to t)
- $\lambda_s = N_0\beta_s$, $\lambda_d = N_0\beta_d$, $\lambda_r = N_0\beta_r$, $s = d = 1/N_0$



$$\frac{dx_k(t)}{dt} = \begin{cases} (s\lambda_s q_k(t) + \lambda_r x_k(t))(1 - x(t) - y(t)) - d\lambda_d x_k(t) \\ -\beta_e x_k(t), \quad \text{for} \quad 0 \le t \le \frac{k}{\lambda_s} + \tau_{i,S}, \\ \\ -d\lambda_d x_k(t) - \beta_e x_k(t), \quad \text{for} \quad \frac{k}{\lambda_s} + \tau_{i,S} < t \le \tau_i. \end{cases}$$

Initial Condition: $x_k(0) = 0$, for all $1 \le k \le M_i$

Fluid-Limit Equations

ACKs replication

- $P_{X_k}(t)$ = Probability that the destination has received coded packet k by time t
- $Q_l^{(i)}(t)$ = Prob. that exactly $i-l$ DoFs have been received by the destination in the current cycle by time t

$$Q_l^{(i)}(t) = \sum_{E\subset\{1,\ldots,M_i\}\,:\,|E|=i-l} \prod_{m\in E} P_{X_m}(t) \prod_{m'\in\{1,\ldots,M_i\}\setminus E} (1-P_{X_{m'}}(t)).$$

$$\frac{dy_l(t)}{dt} = \lambda_r y_l(t)(1-x(t)-y(t)) + d\lambda_d Q_l^{(i)}(t)(1-y_l(t)) \quad \text{for} \quad 0 < t \le \tau_i.$$

Initial Condition: $y_l(0) = 0$, for all $0 \le l \le i-1$

Fluid-Limit Equations

Equations for the CDFs of Packet and ACK Delay

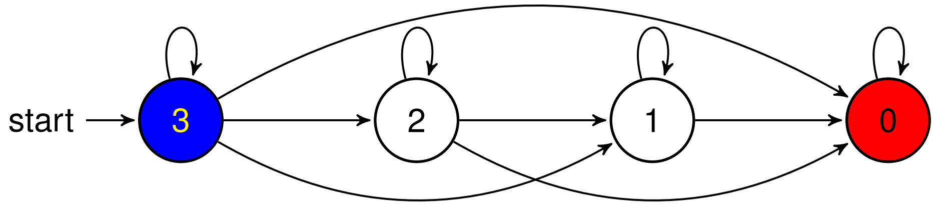
- $P_{X_k}(t)$ = Probability that the destination has received coded packet k by time t
- $P_{Y_l}(t)$ = Probability that the source has received ACK l by time t

$$\frac{dP_{X_k}(t)}{dt} = \lambda_d x_k(t)(1-P_{X_k}(t))$$

$$\frac{dP_{Y_l}(t)}{dt} = \lambda_s y_l(t)(1-P_{Y_l}(t))$$

Initial Condition: $P_{X_k}(0) = 0$, for all $1 \le k \le M_i$,
$P_{Y_l}(0) = 0$, for all $0 \le l \le i-1$.

Combining the Sequence of Cycles



State: Missing DoF at source at the beginning of cycle
P_{ij} = Transition probability from state i to state j, $j = i-1, \dots, 0$

$$P_{ij} \quad = \quad P_{Y_j}(\tau_i) \prod_{l=0}^{j-1} (1 - P_{Y_l}(\tau_i)), \quad \text{for } j < i \text{ and } \quad P_{ii} = 1 - \sum_{j=0}^{i-1} P_{ij}.$$

T_i = mean time to reach state 0 starting from state i

$$T_i = \frac{\sum_{j=1}^{i-1} P_{ij} T_j + \tau_i - \int_0^{\tau_i} P_{i0}(t) dt}{1 - P_{ii}(\tau_i)}.$$

$T_M =$ **Mean Delivery Delay** or **Mean File Transfer Time**

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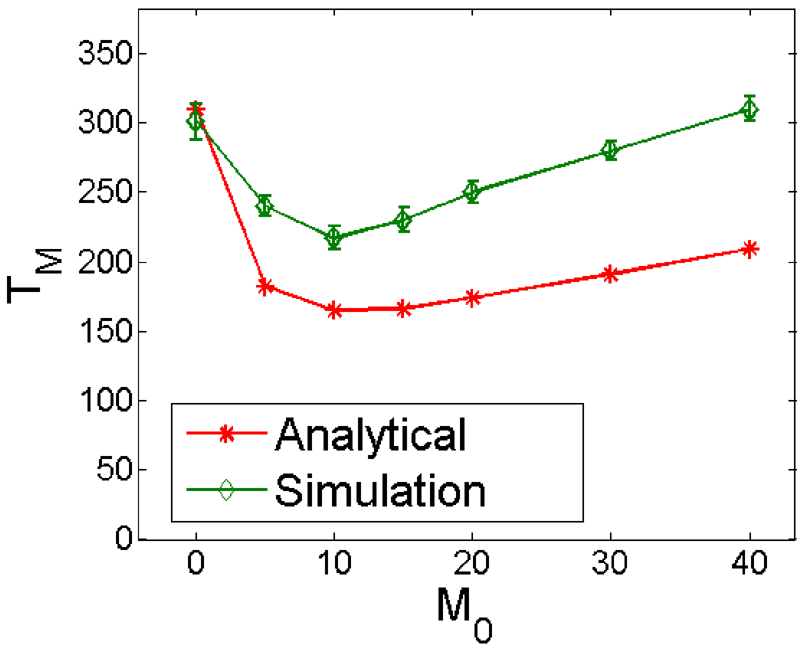
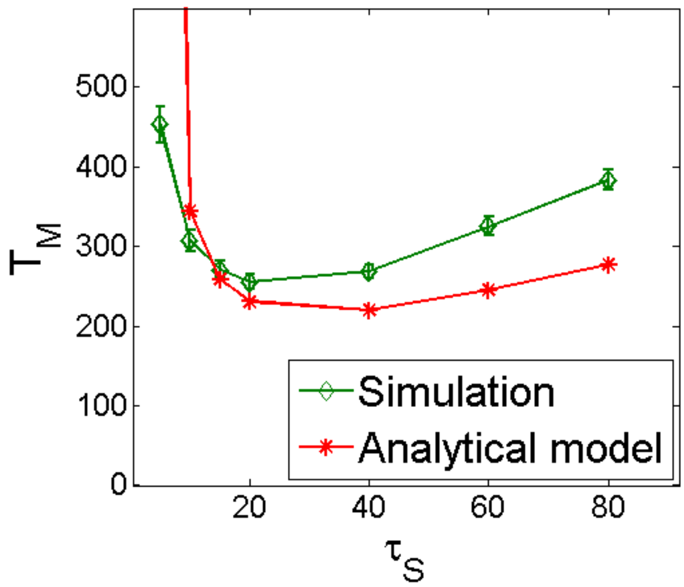
Parameter Setting

- Number of packets to be transferred $M = 10$
- Number of relay nodes $N_0 = 100$
- Inter meeting rate $\beta_s = \beta_d = \beta_r = \beta = 0.005$
- $\tau_{i,S} = \tau_S$, $\tau_{i,W} = \tau_W$, $M_i = M_0 + i$
- M_0 : Level of redundancy
- $\tau_S = \tau_W = \tau_e = 10$, $M_0 = 0, 20$
- Developed a Matlab based simulation
- Random **binary** coefficients are used
- Simulation results averaged over 1000 runs

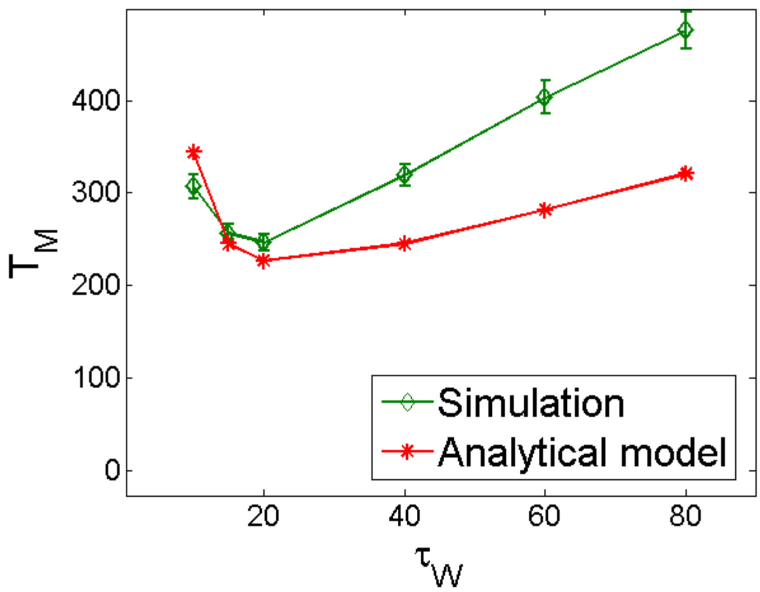
Mean Delivery Delay, T_M, vs. Redundancy, M_0



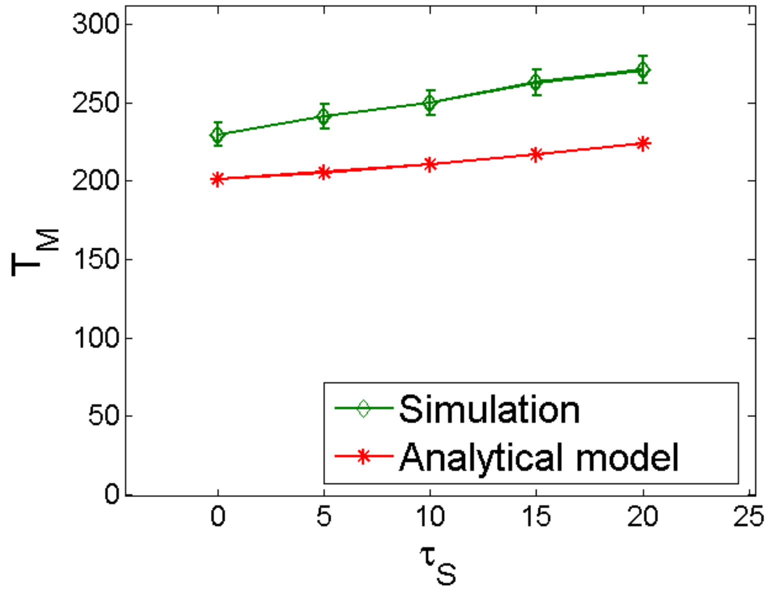
Mean Delivery Delay, T_M, vs. Spread Time, τ_S $M_0 = 0$



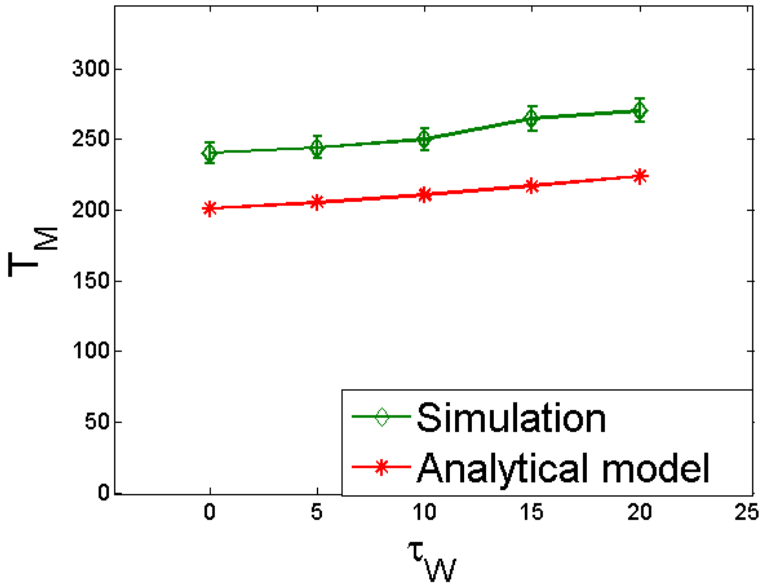
Mean Delivery Delay, T_M, vs. Wait Time, τ_W $M_0 = 0$



Mean Delivery Delay, T_M, vs. Spread Time, τ_S $M_0 = 20$



Mean Delivery Delay, T_M, vs. Wait Time, τ_W $M_0 = 20$



Outline

Our Proposed Transport Framework

Analytical Modeling
- Model Validation

Optimization
- Optimal Mean Delivery Delay

Optimization Procedure

Objective

Minimize the mean time to transfer the complete file, i.e., T_M

Optimization over parameters
- M_i = Number of coded packets to be sent
- $\tau_{i,S}$ = Spreading time
- $\tau_{i,W}$ = ACK wait time

$\forall i,\ i = 1, 2, \ldots, M,\ \forall j,\ i = 0, 1, \ldots, i - 1$

$$\min(T_i) = \frac{\sum_{j=1}^{i-1} P_{ij} \min(T_j) + \tau_i - \int_0^{\tau_i} P_{i0}(t)dt}{1 - P_{ii}(\tau_i)}.$$

Outline

Our Proposed Transport Framework

Analytical Modeling
- Model Validation

Optimization
- Optimal Mean Delivery Delay

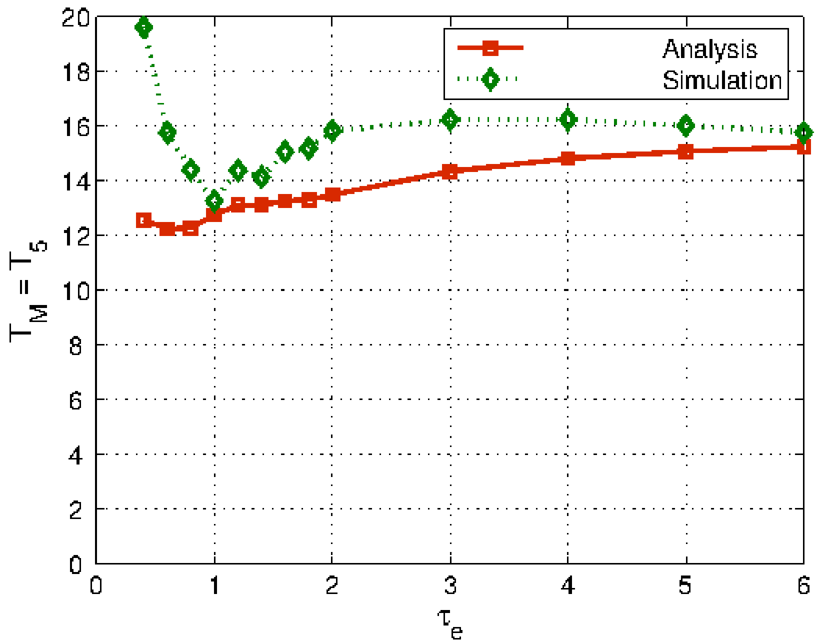
Parameter Setting

- Number of packets to be transferred $M = 5$
- Number of relay nodes $N_0 = 100$
- Inter meeting rate $\beta_s = \beta_d = \beta_r = \beta = 0.05$
- Buffer expiry timeout is varied

We apply **Differential Evolution (DE)** [3] for optimization

[3] R. Storn, K. Price, "Differential evolution - a simple and efficient heuristic for global optimization over continuous spaces," *Journal of Global Optimization*, Vol. 11, pp. 341–359,1997.

Optimal Mean Delivery Delay Vs. Expiry Time



Conclusion

- We proposed a reliable transport framework
  - Random Linear Coding
  - Degree of Freedom (DoF) ACKs
- Derived a fluid-limit model for a single flow
- Optimized the parameters using DE
- Future Work
  - Multiple interacting flows
  - Multiple buffer and buffer management
  - Non-exponential inter-meeting times

Thank You

Timer Implementation

- Let M, N_0, β_s, β_r, β_d be known
- Compute M_i, $\tau_{i,S}$ and $\tau_{i,W}$ off-line for each i
- At source-relay meeting t_k, compute
  - Spreading timeout $t_k + \tau_{i,S}$
  - Cycle timeout $\tau_i = (M_i/\lambda_s) + \tau_{i,S} + \tau_{i,W}$
  - Store in the header of the coded packet
  - Buffer expiry timeout $t_k + \exp(\beta_e)$
- The relay drops the coded packet at $t_k + \exp(\beta_e)$ or τ_i
- At relay-relay meeting t'_k, copy the coded packet to other relay if $t'_k < t_k + \tau_{i,S}$
- At destination-relay meeting, copy the cycle timeout τ_i to the header of the ACK