Mobile Data Offloading through Mobile Social Networks: Performance Analysis and Optimization

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Ad-hoc + Mobile Nodes + Opportunistic communication

- **Nodes = Portable Devices**: smartphones, laptops, etc.
- **Direct communication**: Bluetooth, WiFi direct, etc.
- **Message delivery**: 
  - Direct Transmission (single-hop) OR **Relay-assisted** (multi-hop)
- **Delay tolerance**: no end-to-end path, intermittent connectivity
Use Cases / Applications for MSNs

➢ Lack of infrastructure
  - e.g. after disasters, rural areas, censorship

➢ Content (or service) sharing
  - locally

➢ Mobile data offloading
  - infrastructure + MSN
  - through users’ devices
  - delayed delivery
Mobile Data Offloading: System Model

- Requesters
- Holders

→ Cellular transmission
→ Direct transmission
Goals

**Goal 1**

Given:
- contents popularity (#requesters) & availability (#holders)
- nodes mobility & cooperation (no network control)

**Goal 2**

Under a certain scenario (mobility, popularities, transmission costs):
- content delivery, i.e. cellular transmission or offloading?
- storage, i.e. how many holders (availability )?
- delay tolerance TTL (if possible)
- etc.

analyze performance

optimize offloading cost
Performance Analysis

Goal 1: analyze performance

Metrics:
- expected delivery delay (user)
- delivery probability by TTL (provider)

Content Delivery = Meet any of the holders

Mobility
Availability
Popularity
Performance Analysis: Mobility Model

Mobility = Meeting Events

- Random (or unknown a-priori) & Heterogeneous

\[ t_x: \text{Poisson process} \text{ with rate } \lambda_{ij} \text{ (for a node pair } \{i,j\} \text{)} \]

\[ \lambda_{ij} \text{ drawn from an arbitrary distribution } f_\lambda(\lambda) \text{ (with } E[\lambda_{ij}] = \mu_\lambda) \]

\[ m - \text{holders} \quad \lambda_{i1} \quad \lambda_{i2} \quad \lambda_{i3} \quad \text{node } i \quad n - \text{requesters} \]

Content Delivery = Meet any of the holders

\[ X_M = \sum_{j=1}^{m} \lambda_{ij} \]
Performance Analysis

H: #holders
R: #requesters

\[ H = m \]
\[ R = n \]

\[ H = m \]
\[ R = n-1 \]

\[ \lambda_{(m,n)} \rightarrow (m+1, n-1) \]

\[ \lambda_{(m,n)} \rightarrow (m, n-1) \]

\[ \lambda_{(m,n)} \rightarrow (m, n-1) \]

\[ H(t) \): #holders at time t \]
\[ R(t) \): #requesters at time t \]

\[ \frac{dH(t)}{dt} = p_c \cdot H(t) \cdot R(t) \cdot \mu_\lambda \]

\[ \frac{dR(t)}{dt} = -H(t) \cdot R(t) \cdot \mu_\lambda \]

Mean Field approximation & Fluid Model approximations
Performance Analysis: Results

**Delivery Probability:**

\[
P\{T_d \leq t\} = 1 - \frac{p_c \cdot R_0 + H_0}{p_c \cdot R_0 + H_0 \cdot e^{\mu \lambda (p_c \cdot R_0 + H_0) \cdot t}}
\]

**Expected Delivery Delay:**

\[
E[T_d | TTL] = \ln \left( 1 + \frac{p_c \cdot R_0 - e^{\mu \lambda (p_c \cdot R_0 + H_0) \cdot TTL}}{H_0 + p_c \cdot R_0 \cdot e^{\mu \lambda (p_c \cdot R_0 + H_0) \cdot TTL}} \right)
\]

Dependence on: Mobility & Availability & Popularity
Cost Optimization

GOAL 2  →  optimize offloading cost

• Offloading mechanism: *What can be controlled?*

  - cellular VS opportunistic delivery
  - how many (initial) holders
  - mobility
  - popularities

  - delay tolerance *TTL*
  - user cooperation $\rho_c$
Offloading Costs Model

- initial placement of the content (to holders):
  - $C_{BH}$: to small cells (SCs), from the backhaul
  - $C_{BS}$: to user devices, cellular transmission from BS

- opportunistic delivery:
  - $C_{SC}$: from SC to user
  - $C_{D2D}$: from user to user

- delayed delivery:
  - $C_{BS}^{(TTL)}$: to user devices, cellular transmission from BS
Total Offloading Cost

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- delayed delivery:
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**Total Cost:**

$$C = C_{BH} \cdot H_{SC}(0) + C_{BS} \cdot H_{MN}(0)$$
$$+ (C_{SC} \cdot q + C_{D2D} \cdot (1 - q)) \cdot R_0 \cdot P\{T_d \leq TTL\}$$
$$+ C_{BS}^{(TTL)} \cdot R_0 \cdot (1 - P\{T_d \leq TTL\})$$

→ **Closed form expression** — — \{costs, $H_0$, $R_0$, $\mu$, $TTL$, $p_c$\}
**Total Cost Optimization**

**Optimization problem:**
- deliver many contents (simultaneously): \( \theta \in \mathcal{M} \)
- ...with the minimum cost

\[
\begin{align*}
\min_{H_{SC}, \ H_{MN}, \ \text{TTL}} \left\{ \sum_{\theta \in \mathcal{M}} C^{\theta} \right\}
\end{align*}
\]

\[
\begin{align*}
\text{s.t.} & \quad \forall \theta \in \mathcal{M} : 0 \leq H_{SC}^{\theta}(0) \leq N_{SC} \\
& \quad 0 \leq H_{MN}^{\theta}(0) \leq R^{\theta}(0) \\
& \quad T_{\text{min}} \leq \text{TTL}^{\theta} \leq T_{\text{max}} \\
\text{and} & \quad \sum_{\theta \in \mathcal{M}} H_{SC}^{\theta}(0) \leq \sum_{i \in \mathcal{SC}} Q(i)
\end{align*}
\]

- Total nb of SCs
- Capacity constraint
Example Cases: Optimization Results

Case 1: Offloading only through SCs (i.e. $p_c = 0$)

$$H_{SC}^\theta(0) = \begin{cases} 
N_{SC} & , R^\theta(0) > U \\
\frac{1}{\gamma} \cdot \ln \left( \frac{1}{L} \cdot R^\theta(0) \right) & , L \leq R^\theta(0) \leq U \\
0 & , R^\theta(0) < L 
\end{cases}$$

- **Costs**
- **$\mu_\lambda$**
- **TTL**
- **$N_{SC}$**
- **Total storage capacity**
Example Cases: Optimization Results

**Case 2:** Offloading only through MNs (i.e. no SCs)

\[
H^\theta_{MN}(0) = \frac{R^\theta(0) \cdot \left( \sqrt{\Phi} \cdot e^{\frac{1}{2} \gamma \cdot p_c \cdot R^\theta(0)} - 1 \right)}{e^{\gamma \cdot p_c \cdot R^\theta(0)} - 1}
\]

- **Costs**
- \( \mu_\lambda \)
- **TTL**
- \( p_c \)
Simulation Results

**Case 1**: Offloading only through SCs

**Case 2**: Offloading only through MNs
Conclusions

✓ Performance prediction
  - closed form results

✓ Cost optimization problem
  - numerical (generic case) and analytic (example cases) solutions

➤ Sensitivity analysis
  - effect of different parameters (e.g., mobility, $TTL$, $N_{SC}$)

➤ Network dimensioning
  - e.g. how many SCs? Storage capacity?

➤ Pricing strategies
  - costs, incentives for cooperation ($p_c$) and delay tolerance ($TTL$)
Related Publications


Pavlos Sermpezis, Thrasyvoulos Spyropoulos, "Not all content is created equal: Effect of popularity and availability for content-centric opportunistic networking", Proc. ACM MobiHoc, August 2014

https://sites.google.com/site/pavlossermpezis/
“Understanding (analytically) the effects of social heterogeneity on the performance of MSNs”

- Mobility Heterogeneity
- Social Selfishness
- Traffic Heterogeneity
- Interest patterns
Research in MSNs: Mobility Heterogeneity

- **Models:**
  Homogeneous (unrealistic, simple) VS Heterogeneous (realistic, complex) models

- Trade-off between realism & complexity:
  *Heterogeneous rates* (in a probabilistic way) + *Random graph theory*

- Asymptotic analysis & closed form approximations

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\[
\lambda_{ij} \sim f_\lambda(\lambda)
\]
Research in MSNs: Social Selfishness

- **Selfishness** (or cooperation) related to *social ties*
- **Social ties** related to *mobility*

> **Selfishness** related to *mobility*

\[ p_{ij} = p(\lambda_{ij}) \]

- Closed form results for performance prediction:
  1. selfishness scenarios
  2. cooperation policies  \( \rightarrow \) optimization!
Research in MSNs: Traffic Heterogeneity

- **Joint effect** of mobility/traffic heterogeneity

- Generic model and closed form results
  \[ E[\tau_{ij}] = \tau(\lambda_{ij}) \]

- Implications for opportunistic networking:
  - Evaluation of routing protocols
  - End-to-end applications
  - Content-centric applications

![Graph 1](image_url1)

![Graph 2](image_url2)
Research in MSNs: Interest Patterns

- Generic model & closed form results: effects of *popularity* and *availability*

\[
P\{T_M \leq TTL\} = 1 - \frac{E_p[n \cdot \sum_m E_m \lambda \left[ e^{-x \cdot TTL} g(m|n) \right]}{E_p[n]}.
\]

→ mobility \( f_\lambda(\lambda) \), availability \( g(m|n) \), popularity \( P_p(n) \)

- Dataset Analysis: Realistic interest patterns

<table>
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<th>Content Type</th>
<th>Network Size</th>
<th>Pareto</th>
<th>( \alpha )</th>
<th>Gamma</th>
<th>( CV )</th>
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</tbody>
</table>
THANK YOU !!!
Content-centric Applications: System model

- **Availability:** #Holders
- **Popularity:** #Requesters
Simulation Results: Delivery Probability
Simulation Results: Offloading Cost
Example Cases: Optimization Results

Case 1: Offloading only through SCs

**Result 19.** Under a base scenario ($p_c = 0, H_{MN}(0) = 0$), the initial allocation $H_{SC}$ that minimizes the total cost, is given by

$$H_{SC}^\theta(0) = \begin{cases} 
N_{SC} & , R^\theta(0) > U \\
\frac{1}{\gamma} \cdot \ln \left( \frac{1}{L} \cdot R^\theta(0) \right) & , L \leq R^\theta(0) \leq U \\
0 & , R^\theta(0) < L
\end{cases}$$

with \( \gamma = \mu \cdot TTL \), \( L = \frac{1}{\gamma \Phi} \cdot \left( 1 + \frac{\lambda_0}{C_{BH}} \right) \), \( U = L \cdot e^{N_{SC}} \cdot e^{TTL} \cdot \Phi = \frac{C_{BS}^{(TTL)} - C_{SC}}{C_{BH}} \), and

$$\lambda_0 = \inf \left\{ \lambda_0 \geq 0 : \sum_{\theta \in M} H_{SC}^\theta(0) \leq \sum_{i \in SC} Q(i) \right\}$$
Case 2: Offloading only through MNs

Result 20. Under an opportunistic MN-MN scenario ($p_c > 0$, $H_{SC}(0) = 0$), the initial allocation $H_{MN}$ that minimizes the total cost, is given by

$$H_{MN}(0) = \begin{cases} R^\theta(0), & R^\theta(0) \leq OPT^\theta \\ OPT^\theta, & 0 \leq OPT^\theta < R^\theta(0) \\ 0, & OPT^\theta < 0 \end{cases}$$

where $OPT^\theta = \frac{R^\theta(0) \cdot (\sqrt{\Phi'} \cdot e^{\frac{1}{2} e \gamma p_c \cdot R^\theta(0)} - 1)}{e \gamma p_c \cdot R^\theta(0) - 1}$, and $\Phi' = \frac{C_{BS}(TTL) - C_{D2D}}{C_{BS} - C_{D2D}}$ and $\gamma = \mu \lambda \cdot TTL$. 
Research in MSNs

- **Mobility Heterogeneity**
  - *homogeneous VS heterogeneous* models
  - Trade-off between realism & complexity:
    - *Heterogeneous rates* (in a probabilistic way) + *Random graph theory*
  - Asymptotic analysis & closed form approximations

- **Social Selfishness**
  - *Selfishness* (or cooperation) related to *social ties / mobility*
  - Generic model and closed form results

- **Traffic Heterogeneity**
  - *Joint effect* of mobility/traffic heterogeneity
  - Generic model and closed form results

- **Interest patterns**
  - Generic model & closed form results: effects of *popularity* and *availability*
  - Dataset Analysis: Realistic interest patterns