Opportunistic Content-Centric Communications: Modeling, Analysis and Applications

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Opportunistic Communications

• Opportunistic Network
  - Mobile Devices: smartphones, laptops, etc.
  - Direct communications: Bluetooth, WiFi direct, etc.

• Content-Centric Applications
  - Mobile Data Offloading
  - Content Sharing (p2p)
  - Service Composition
Mobile Data Offloading: System Model

• Hybrid Network
  - Mobile nodes (M) & Infrastructure (I)
  - Long range communications (I-M) & Short range communications (M-M, I-M)

• Communication Scenario
  1. Content Provider
  2. Nodes interested in content items
     - one node – multiple contents
     - many nodes – one content
  3. Content delivery
     - Direct (long range transmission)
     - Opportunistic (short range transmission) ➔ Offloading
Mobile Data Offloading: System Model
Communication Characteristics

- **Requester**: a node interested in a given content
- **Holder**: a node that (a) has the content, (b) relays it to requesters
COMMUNICATION
- **Time Invariant Interest**
  - no loss of interest, no new requesters
- **Any Initial Allocation**
  - to requesters / relays / hybrid
- **Dropping policy**
  - each holder drops contents with rate $\lambda_d$ - Poisson process
- **Cooperation policy**
  - Full / No / Partial (each requester becomes holder with probability $p_c$)

MOBILITY
- Meeting s between each node pair $\{i,j\}$ – Poisson process with rate $\lambda_{ij}$
- Mean value of meeting rates – $\mu_\lambda$
Distribution of a Single Content
Analysis: Markov Chain

H: number of *holders*
R: number of requesters

**λ**\((m,n)\rightarrow(m+1,n-1)\) ≈ \(p_c \cdot H \cdot R \cdot \mu\)

**λ**\((m,n)\rightarrow(m,n-1)\) ≈ \((1-p_c) \cdot H \cdot R \cdot \mu\)

**λ**\((m,n)\rightarrow(m-1,n)\) ≈ \(H \cdot \lambda_d\)
**Analysis: Fluid Model**

**H(t):** number of *holders* at time *t*

**R(t):** number of requesters at time *t*

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

**ODEs:**

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

**Initial conditions:**

\[H(0) = H_0\]

\[R(0) = \begin{cases} R_0 & \text{To relays} \\ R_0 - H_0 & \text{To requesters} \end{cases}\]

→ **Solutions** for ... **H(t)** and **R(t)** (closed form or numerical)
Results

\( H(t) \): number of *holders* at time \( t \)

\( T_d \): content *delivery delay* to a requester

Delivery Probability:

\[
P\{T_d \leq TTL\} = 1 - e^{-\mu \int_0^{TTL} H(\tau) d\tau}
\]

Expected Delivery Delay:

\[
E[T_d] = \int_0^\infty e^{-\mu \int_0^t H(\tau) d\tau} \cdot dt
\]

**Examples**

e.g.1 \( p_c = 0, \lambda_d = 0 \)

\[
P\{T_d \leq TTL\} = 1 - e^{-\mu \cdot H_0 \cdot TTL}
\]

e.g.2 \( \lambda_d = 0, R(0) = R_0 \)

\[
E[T_d] = \frac{1}{p_c \cdot R_0 \cdot \mu \lambda} \cdot ln \left( 1 + \frac{p_c \cdot R_0}{H_0} \right)
\]
An Application Example: Cost Optimization

Mobile Data Offloading Scenario
1) \( R_0 \) requesters
2) \( CP \) sends content to \( H_0 \) holders
3) Opportunistic content sharing, till time TTL
4) \( CP \) directly sends the content to requesters that have not received it by TTL

Costs per transmission
• \( \Phi_I \): from \( CP \) to a mobile/infrastructure node
• \( \Phi_M \): from a relay (mobile or infrastructure) node to a mobile node

Objective
Minimize total transmission cost \( U \), s.t. all requesters receive the content by TTL

RESULTS
• Total Cost:
  \[
  U = \Phi_I \cdot H_0 + (\Phi_I - \Phi_M) \cdot R_0 \cdot e^{-\mu \cdot \int_0^{TTL} H(\tau) d\tau} + \Phi_M \cdot R_0
  \]
• Case Study \( p_c=0, \lambda_d=0 \)
  \( H_0^* = \frac{1}{\mu \cdot TTL} \cdot \ln \left( \frac{1 + \Phi_I}{\Phi_M} \right) \mu \cdot TTL \cdot R_0 \)
Extension: Time-Varying Interests

• **Model**
  - Content with lifetime TTL
  - At time $t < 0$, no requesters exist
  - **New requesters** appear with rate $\lambda(t)$, $0 \leq t \leq \text{TTL}$

• **Result**
  Probability a requester to access the content by time TTL

\[
P\{T_d \leq \text{TTL}\} = 1 - \frac{\int_0^{\text{TTL}} \lambda(t) \cdot e^{-\mu \lambda \int_0^{\text{TTL}} H(\tau) d\tau} \cdot dt}{\int_0^{\text{TTL}} \lambda(t) \cdot dt}
\]
Distribution of Multiple Contents
• **Content Popularity**
  The number of requesters interested in the content, i.e. \( R_0 \)

• **Popularity Distribution**: \( P(n) = P\{R_0 = n\} \)
  - usually \( P(n) \) can be approximated with a *Pareto* distribution

- 10 requesters
- 4 requesters
- 2 requesters
Communication Scenario - **Initial Allocation:**
- For each content with popularity \( n \), the CP assigns \( H_0 = g(n) \) initial holders
- \( g(n): [1,N] \to [0,N] \)

**Delivery Probability:**
\[
P\{T_d \leq TTL\} = 1 - \frac{1}{E_p[n]} \cdot E_p \left[ n \cdot e^{-\mu \cdot \int_0^{TTL} H(\tau|n)d\tau} \right]
\]

**Expected Delivery Delay:**
\[
E[T_d] = \frac{1}{E_p[n]} \cdot E_p \left[ n \cdot \int_0^{\infty} e^{-\mu \cdot \int_0^{t} H(\tau|n)d\tau} \right]
\]

**Examples**

\[ p_c = 0, \lambda_d = 0 \]
\[
P\{T_d \leq TTL\} = 1 - \frac{1}{E_p[n]} \cdot E_p \left[ n \cdot e^{-\mu \lambda \cdot g(n) \cdot TTL} \right]
\]

\[ \lambda_d = 0, R(0) = R_0 \]
\[
E[T_d] = \frac{1}{\mu \lambda \cdot E_p[n]} \cdot E_p \left[ \frac{n}{g(n)} \right]
\]
THANK YOU !!!