The Virtue of Patience: Offloading Topical Cellular Content through Opportunistic Links

IEEE MASS 2013

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[1] Indiana University-Purdue University Indianapolis

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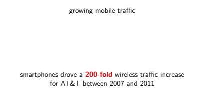
growing mobile traffic

smartphones drove a **200-fold** wireless traffic increase
for AT&T between 2007 and 2011



growing mobile traffic

smartphones drove a **200-fold** wireless traffic increase
for AT&T between 2007 and 2011

- there is a clear need for more bandwidth.
- a question to ask is “what can be done to alleviate this situation besides service providers’ investment?”

mobile data offloading

goal

- alleviate pressure of growing mobile traffic
- an alternative to mobile infrastructure channel

technical readiness

- increasing infrastructure-less proximity-channel bandwidth at little cost
    - NFC, Wi-Fi Direct, Bluetooth 3
- more intuitive interface
    - contact-less transfer

idea

- offload **cellular** traffic through the **proximity** channel

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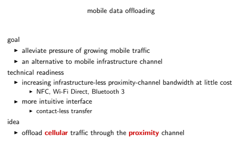
└─mobile data offloading



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problem formulation

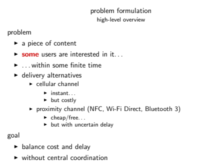
high-level overview

problem

- a piece of content
- **some** users are interested in it. . .
- . . . within some finite time
- delivery alternatives
    - cellular channel
        - instant. . .
        - but costly
    - proximity channel (NFC, Wi-Fi Direct, Bluetooth 3)
        - cheap/free. . .
        - but with uncertain delay

goal

- balance cost and delay
- without central coordination



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- here is a high-level description of the problem
- we will refine the elements later

problem with central coordination is both efficiency and privacy, which drive the development of P2P networks

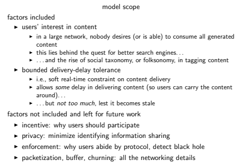
model scope

factors included

- users' interest in content
  - in a large network, nobody desires (or is able) to consume all generated content
  - this lies behind the quest for better search engines. . .
  - . . . and the rise of social taxonomy, or folksonomy, in tagging content
- bounded delivery-delay tolerance
  - i.e., soft real-time constraint on content delivery
  - allows *some* delay in delivering content (so users can carry the content around). . .
  - . . . but *not too much*, lest it becomes stale

factors not included and left for future work

- incentive: why users should participate
- privacy: minimize identifying information sharing
- enforcement: why users abide by protocol, detect black hole
- packetization, buffer, churning: all the networking details



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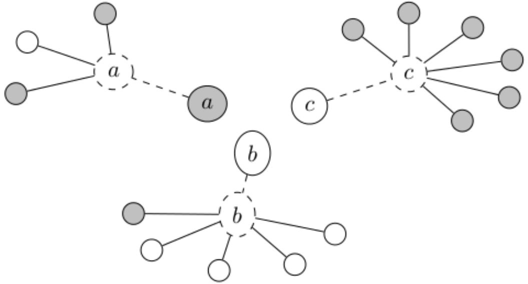
- in any model, there are factors to include and there are others to exclude
- let us set that straight here

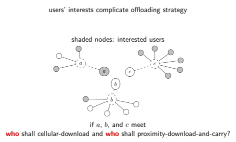
users’ interests complicate offloading strategy

shaded nodes: interested users



if a, b, and c meet

who shall cellular-download and **who** shall proximity-download-and-carry?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if a, b, and c meet
who shall cellular-download and **who** shall proximity-download-and-carry?

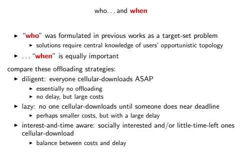
Though b has more acquaintances than a does and therefore, in some sense, is more socially important, few of b’s acquaintances are interested in the content, when compared with those of a: It is more cost effective for a to download and carry the content than b. In another comparison, c is more socially important than a, and most of c’s acquaintances are interested in the content: Though c is not interested in the content, if c downloads and carries the content, c can serve more users within a reasonable time than a can. In general, a cost-effective offloading strategy involves an interplay between users’ interests and their social importance.

who. . . and **when**

- “**who**” was formulated in previous works as a target-set problem
    - solutions require central knowledge of users’ opportunistic topology
- . . . “**when**” is equally important

compare these offloading strategies:

- diligent: everyone cellular-downloads ASAP
    - essentially no offloading
    - no delay, but large costs
- lazy: no one cellular-downloads until someone does near deadline
    - perhaps smaller costs, but with a large delay
- interest-and-time aware: socially interested and/or little-time-left ones cellular-download
    - balance between costs and delay



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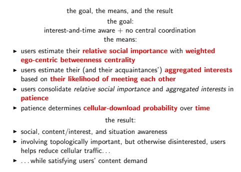
the goal, the means, and the result

the goal:
interest-and-time aware + no central coordination
the means:

- users estimate their **relative social importance** with **weighted ego-centric betweenness centrality**
- users estimate their (and their acquaintances') **aggregated interests** based on **their likelihood of meeting each other**
- users consolidate *relative social importance* and *aggregated interests* in **patience**
- patience determines **cellular-download probability** over **time**

the result:

- social, content/interest, and situation awareness
- involving topologically important, but otherwise disinterested, users helps reduce cellular traffic. . .
- . . . while satisfying users' content demand



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model

elements

- content tagged by multiple tags (topics)
- I_u: tags interested by smartphone user u
- f_g: content g's freshness/expiration date
- after content is centrally released, users choose from either:
    - cellular download (instant but costly)
    - waiting for proximity-download (free but with an uncertain delay)

assumptions

- proximity links are free
    - epidemic propagation of content on proximity links
    - ignore packetization and buffer management
- users follow the protocol
    - honestly share their interests with neighbors
    - cellular download even it is only for the greater good
    - about privacy, incentive, and enforcement

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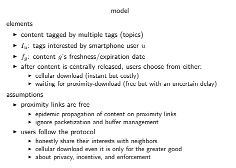
Patience in Mobile Offloading

└─model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design elements
temporal tie strength

- u estimates frequency of meeting its neighbors U_u based on historic encounters
- $\hat{s}_u(v)$: average consecutive-encounter delay between nodes u and v
  details
- **temporal tie strength** (tie) $s_u(v) \in [0,1]$:

$$s_u(v) = \begin{cases} \exp(-\alpha_s \hat{s}_u(v)) & s_u(v) \in [0,+\infty), \\ 0 & s_u(v) = +\infty, \end{cases} \tag{1}$$

  1 ⇒ strong tie; 0 ⇒ weak tie
- $\alpha_s > 0$: a scaling parameter to prevent $s_u(v)$ from dropping too fast from increasing $\hat{s}_u(v)$

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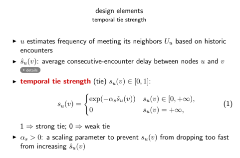

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- G_u: u's neighborhood weighted by $\hat{s}_u(v)$
- **weighted ego-centric betweenness centrality** $\beta_u \in [0,1]$—the portion of shortest path passing through u:

$$\beta_u = \begin{cases} \dfrac{\sum\limits_{v,w\in U_u, v\neq w} [p(v,w)]}{2\binom{|U_u|}{2}} & |U_u| \geq 2, \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

- $p(v,w)$: "(v,u,w) is a shortest path between v and w"

$$[p] = \begin{cases} 1 & p \text{ is true,} \\ 0 & p \text{ is false.} \end{cases}$$

Patience in Mobile Offloading

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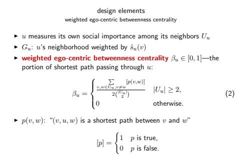

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interest aggregation

- u aggregate its and its neighbors' interests on content with tag g
- I_v: v's interested tags (reported to u upon their encounters)
- u's **aggregated interest** $i_u(g) \geq 0$ on tag g:

$$i_u(g) = [g \in I_u] + \sum_{v \in U_u} s_u(v)[g \in I_v]. \tag{3}$$

- $i_u(g) < 1$ only if $g \notin I_u$.

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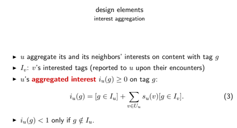

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design elements

patience and probabilistic cellular downloading strategy

- u's **patience** $p_{u,g} : [0,1] \to [0,1]$ for tag g:

$$p_{u,g}(x) = \begin{cases} \left(1 - e^{-\alpha_i i_u(g)}\right) x^{\alpha_\beta^{(1-2\beta_u)}} & g \in I_u, \\ \left(1 - e^{-\alpha_i i_u(g)}\right) (1-x)^{\alpha_\beta^{(1-2\beta_u)}} & g \notin I_u. \end{cases} \tag{4}$$

- $\alpha_i > 0$ and $\alpha_\beta > 1$: scaling parameters for $i_u(g)$ and β_u

At the moment $t + x \cdot f_g$ ($x \in [0,1]$) between:

- the time t that u first learns about a piece of content with tag g and
- the time $t + f_g$ that the content becomes stale for u

u cellular-downloads the content with a probability of:

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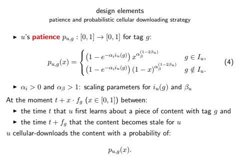

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analysis

probabilistic cellular-download strategy properties

Property

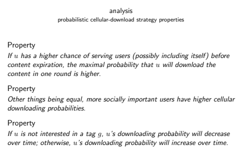
If u has a higher chance of serving users (possibly including itself) before content expiration, the maximal probability that u will download the content in one round is higher.

Property

Other things being equal, more socially important users have higher cellular downloading probabilities.

Property

If u is not interested in a tag g, u's downloading probability will decrease over time; otherwise, u's downloading probability will increase over time.



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the intuition behind $i_u(g)$ is exactly to reflect the chances of u being able to serve content in time.

The intuition behind Property 2 is that a more socially important user has better chance of meeting others, and passing on the downloaded content. Therefore, letting them download with higher probabilities may help offloading the cellular traffic to the proximit link.

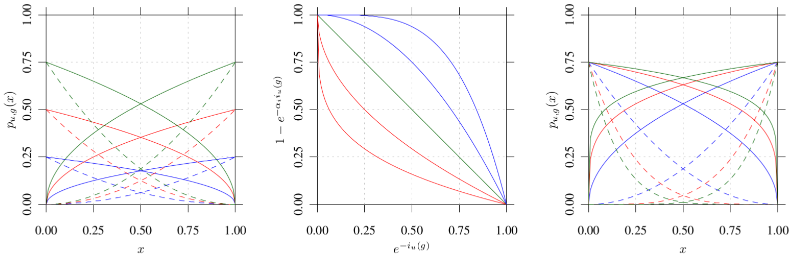
The intuition behind Property 3 is as follows.

- If u is not interested in a tag g, u is being purely altruistic in downloading content with g. u can start downloading with a high probability in the hope that he can forward the content to others when they meet later. With the chances of meeting others (and hence forwarding the content to others through the proximity link) dwindling over time, the value of celluar downloading decreases. This is reflected b the monotonically decreasing downloading probability in the second case in Equation (4).
- Conversely, if u is interested in a tag g, u is helping both himself and others in downloading content with g. u can afford to start downloading with a low probability in the hope that he can receive the content from another user who has the content, and thus, save cellular bandwidth. With the chances of meeting other (and hence receiving the content from others through the proximity link) dwindlin over time, u becomes increasingly *impatient* in waiting. This is reflected by the monotonically increasing downloading probability in the first case in Equation (4).

analysis

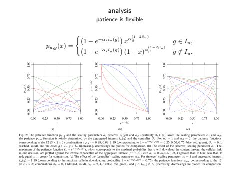
patience is flexible

$$p_{u,g}(x) = \begin{cases} \left(1 - e^{-\alpha_i i_u(g)}\right) x^{\alpha_\beta^{(1-2\beta_u)}} & g \in I_u, \\ \left(1 - e^{-\alpha_i i_u(g)}\right) (1-x)^{\alpha_\beta^{(1-2\beta_u)}} & g \notin I_u. \end{cases}$$



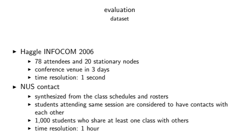
(a) (b) (c)

Fig. 2: The patience function $p_{u,g}$ and the scaling parameters α_i (interest $i_u(g)$) and α_β (centrality β_u). (a) Given the scaling parameters α_i and α_β, the patience $p_{u,g}$ function is jointly determined by the aggregated interest $i_u(g)$ and the centrality β_u. For $\alpha_i = 1$ and $\alpha_\beta = 2$, the patience functions corresponding to the 12 ($3 \times 2 \times 2$) combinations $i_u(g) = 0.29, 0.69, 1.39$ (corresponding to $1 - e^{-\alpha_i i_u(g)} = 0.25, 0.50, 0.75$; blue, red, green), $\beta_u = 0, 1$ (dashed, solid), and the cases $g \in I_u, g \notin I_u$ (increasing, decreasing) are plotted for comparison. (b) The effect of the (interest) scaling parameter α_i. The maximum of the patience function $(1 - e^{-\alpha_i i_u(g)})$, which corresponds to the maximal probability that u will download the content through the cellular link in one decision, are plotted against the inverse exponential of the aggregated interest $(e^{-i_u(g)})$ with $\alpha_i = 0.25, 0.5, 1, 2, 4$ (greater than 1: blue; less than 1: red; equal to 1: green) for comparison. (c) The effect of the (centrality) scaling parameter α_β. For (interest) scaling parameter $\alpha_i = 1$ and aggregated interest $i_u(g) = 1.39$ (corresponding to the maximal cellular downloading probability $1 - e^{-\alpha_i i_u(g)} = 0.75$), the patience functions $p_{u,g}$ corresponding to the 12 ($2 \times 2 \times 3$) combinations $\beta_u = 0, 1$ (dashed, solid), $\alpha_\beta = 2, 4, 6$ (blue, red, green), and $g \in I_u, g \notin I_u$ (increasing, decreasing) are plotted for comparison.



evaluation
dataset

- Haggle INFOCOM 2006
    - 78 attendees and 20 stationary nodes
    - conference venue in 3 days
    - time resolution: 1 second
- NUS contact
    - synthesized from the class schedules and rosters
    - students attending same session are considered to have contacts with each other
    - 1,000 students who share at least one class with others
    - time resolution: 1 hour



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evaluation
comparison

- 3 variants of the patience-based strategy

		eager	moderate	lazy
Haggle	α_i	0.5	0.1	0.05
	α_β	2		
	α_s	0.01		
NUS	α_i	0.05	0.03	0.01
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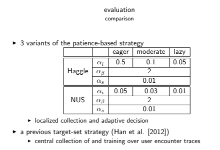
	α_s	0.01		

  - localized collection and adaptive decision
- a previous target-set strategy (Han et al. [2012])
  - central collection of and training over user encounter traces



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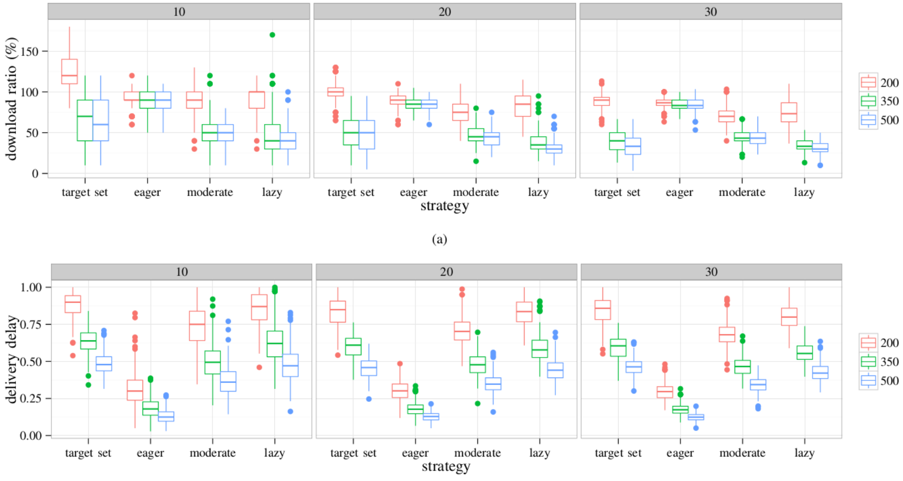
evaluation

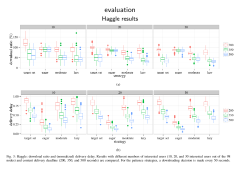
Haggle results



(a)

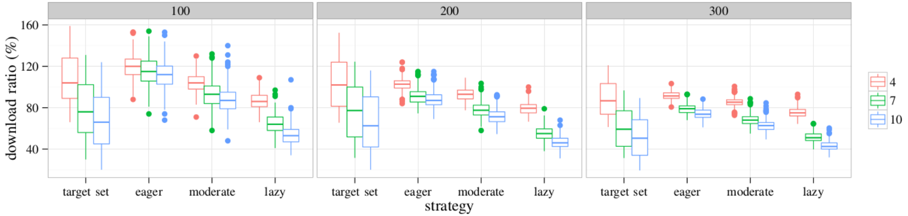
(b)

Fig. 3: Haggle: download ratio and (normalized) delivery delay. Results with different numbers of interested users (10, 20, and 30 interested users out of the 98 nodes) and content delivery deadline (200, 350, and 500 seconds) are compared. For the patience strategies, a downloading decision is made every 50 seconds.



evaluation

NUS results



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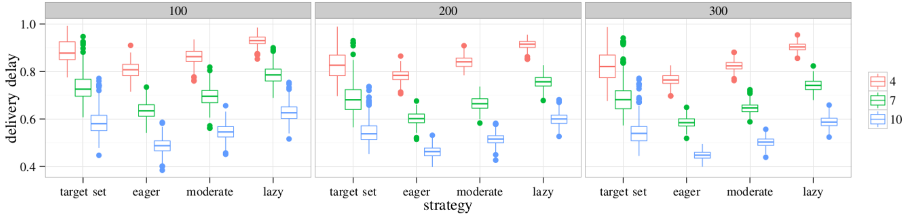

(b)

Fig. 4: NUS: download ratio and (normalized) delivery delay. Results with different numbers of interested users (100, 200, and 300 interested users out of the 1,000 nodes) and content delivery deadline (4, 7, and 10 hours) are compared. For the patience strategies, a downloading decision is made every 1 hour.

Patience in Mobile Offloading

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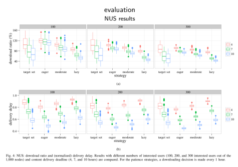
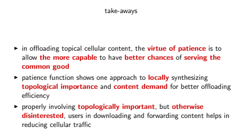
└evaluation



take-aways

- in offloading topical cellular content, the **virtue of patience** is to allow **the more capable** to have **better chances** of **serving the common good**
- patience function shows one approach to **locally** synthesizing **topological importance** and **content demand** for better offloading efficiency
- properly involving **topologically important**, but **otherwise disinterested**, users in downloading and forwarding content helps in reducing cellular traffic



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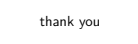
Patience in Mobile Offloading



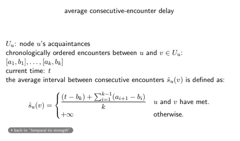
thank you

average consecutive-encounter delay

U_u: node u's acquaintances
chronologically ordered encounters between u and $v \in U_u$:
$[a_1, b_1], \ldots, [a_k, b_k]$
current time: t
the average interval between consecutive encounters $\hat{s}_u(v)$ is defined as:

$$\hat{s}_u(v) = \begin{cases} \dfrac{(t - b_k) + \sum_{i=1}^{k-1}(a_{i+1} - b_i)}{k} & u \text{ and } v \text{ have met.} \\ +\infty & \text{otherwise.} \end{cases}$$

▸ back to "temporal tie strength"



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