Content-Update Process Performance under Energy Saving Schemes in Mobile Opportunistic Networks

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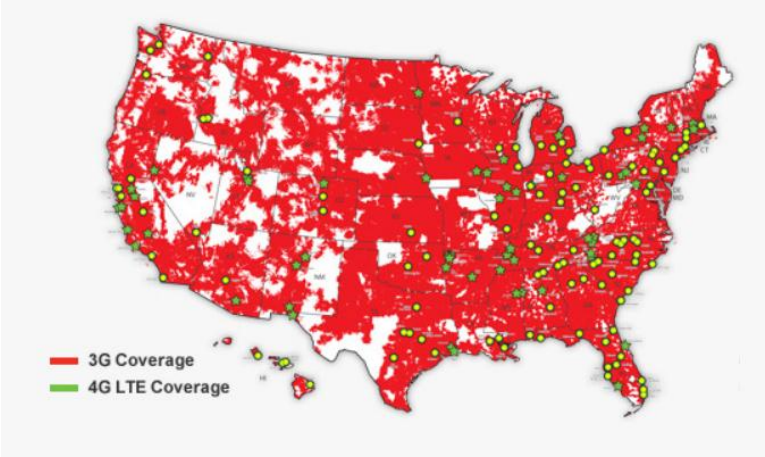
Mobile Hand-Held Devices

- Receive a popularity over recent years
  (e.g., smart-phones and tablets)
- Allow users to obtain content almost without Time and Space limitations
- How? By using a wide-area communication infrastructure
  (e.g., 3G Network Coverage in North America)

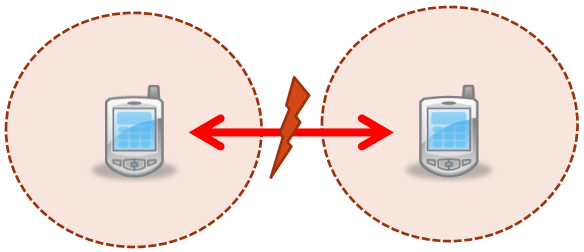


Current Challenges and Alternatives

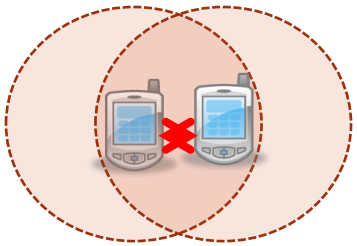
- The popularity of mobile devices induces severe traffic demands on cellular networks
  - The demand almost reached the limit of network capacity
  - Wireless companies such as Verizon and AT&T recently suspended their unlimited data plan service
- Mobile Ad-hoc NETwork (MANET) research can help to reduce the traffic burdens
  - Smart-phone and tablets have an option for ad-hoc communications (e.g., Bluetooth)
  - But, these are rarely used as devices are operated under a centralized network (e.g., 3G cellular)
- How can we utilize the ad-hoc communication option?
  - Already, MANET research has a lot of results
  - The difference of our work? Consider the Energy-Constraint of devices

Information Delivery in MANETs

- Contact pattern among users:
  - Most important in the sense of supporting information delivery chances

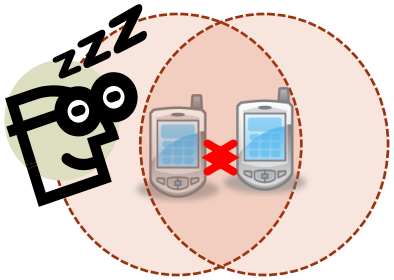


No contact:
No Delivery



Contact:
Delivery

- Energy-Constraint issue in mobile hand-held devices:
  - Devices are allowed to use energy-saving strategies (e.g., control the sleep/awake status of devices)
  - This severely affects the information delivery pattern
  - Why?
    - The sleep status of devices prevents the delivery of information even when a contact occurs.

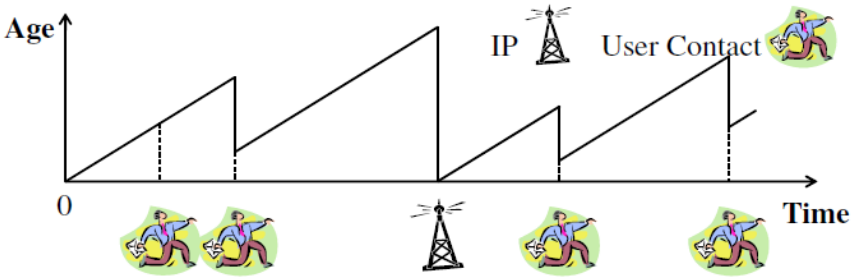


No Delivery

Content Update Process

- To distribute "Age Sensitive Content"
  - The importance of content decreases with time after its generation (e.g., news, tweets and traffic information)
  - Users want to have the more recent content.
- Content-Update Process:
  - One 'Information Provider (IP)' generates a content continuously and 'Mobile users' obtain the content through opportunistic contacts.
  - Content Age (A(t)) distinguishes the freshness of content
  - Content Update Process: When each contact occurs, they compare their content age and share the lesser of the two (i.e., $\min\{A_{i(t)}, A_{j(t)}\}$)

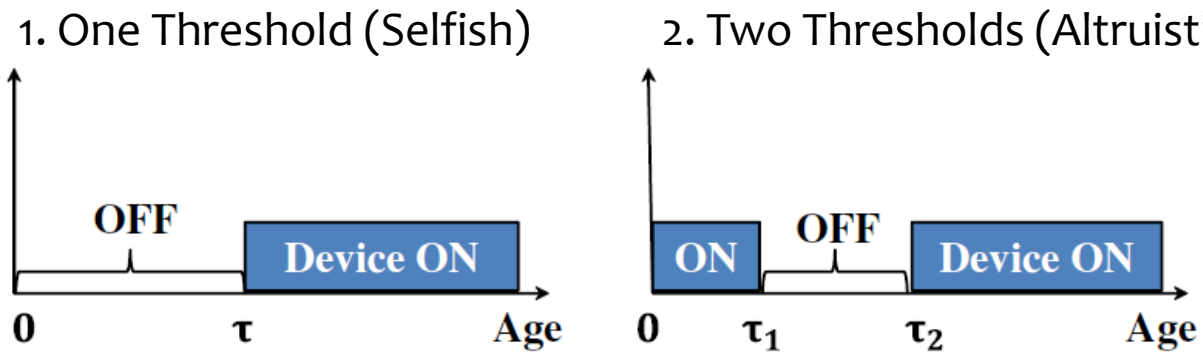
Example) The age variation of one user under content-update process



(a) Content Update Process

Energy-Saving Rules

- The performance of content update process can be severely changed by the device sleep/awake rules
- Trade-offs between content freshness and energy consumption
- Our study provides its analysis and validation
- Two energy-saving sleep/awake control rules:
  - For age-sensitive content propagation, the own content age of users can be utilized to decide sleep/awake



(b) Device ON/OFF Control Rules

Research Questions and Goals

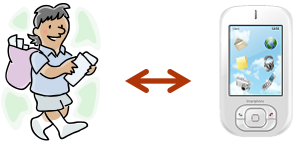
- Question:
  - "How the performance of content updates varies according to the energy-saving rules of device?"
- Challenges:
  - Quantifying the trade-offs between content freshness and energy consumption
    - The trade-off itself is intuitive. But, measuring the degree is difficult
  - Fair Comparison among different sleep/awake rules
    - Using different sleep/awake rules makes changes both on content freshness and energy consumption at the same time
- We do:
  - Mean-field based analysis
    - Provide the content freshness of users (both distribution and its mean freshness)
  - Provide an energy normalization method
    - By using ergodicity, normalize the energy consumption of different rules.
    - This provides the fair comparison between different rules

Part I. Content age distribution of users

- We analyze:
  - The content age (i.e., freshness) distribution of users under the use of device sleep/awake rules.

- Network assumptions:
  - 1 Information provider (IP) and n mobile users
  - Contact rate

(between users) : inter-any-contact rate λ



(between IP and user) : inter-contact rate γ

Part I. Content age distribution of users

- How we have the distribution?
  - Mean-field based ODE (Ordinary Differential Equation)
  - Brief ODE construction procedures:

    (Please, see our paper for details)
    - Select one user and consider its content age dynamics during small time interval ϵ
    - Utilize symmetric interactions and asymptotic independence among users (This allows us to ignore user distinctions)
  - For energy-saving rules, those ODEs are non-linear. But, they have a unique closed-form solution.

$$\mathbf{F}_{S1}(a) = \begin{cases} e^{-\gamma a} & , a \in (0, \tau] \\ \frac{e^{-(\gamma+\lambda F(\tau))a}}{\frac{\lambda F(\tau)}{\gamma+\lambda F(\tau)} e^{-(\gamma+\lambda F(\tau))a} + \mathbf{c}} & , a \in (\tau, \infty] \end{cases} \quad (8)$$

where $\mathbf{c} = \frac{1}{F(\tau)}(1 - \frac{\lambda F^2(\tau)}{\gamma+\lambda F(\tau)}) e^{-(\gamma+\lambda F(\tau))\tau}$ and $\mathbf{F}(\tau) = e^{-\gamma\tau}$.

The content age distribution (CCDF) under one threshold device sleep/awake

$$\mathbf{F}_{S2}(a) = \begin{cases} \frac{(\gamma+\lambda)e^{-(\gamma+\lambda)a}}{\lambda e^{-(\gamma+\lambda)a} + \gamma} & , a \in (0, \tau_1] \\ e^{-\gamma a} + \mathbf{c}_1 & , a \in (\tau_1, \tau_2] \\ \frac{e^{M_1 a}}{-\frac{M_2}{M_1} e^{M_1 a} + \mathbf{c}_2} & , a \in (\tau_2, \infty) \end{cases} \quad (11)$$

The content age distribution (CCDF) under two threshold device sleep/awake

Part II. Energy Normalization Method

- Different sleep/awake rules induces:
  - The different content freshness of users
  - The different energy consumption of devices
- For fair performance comparisons:
  - Normalize either freshness or energy consumption
  - We normalize an energy consumption. How?
    - Using *mean ergodicity* (In steady-state, time-average and space-average are same)
    - To know the closed-form distribution ($F_{S1}(a)$ and $F_{S2}(a)$) allows us to compute the space average of device awake condition (See our paper for details).

$$\mathbf{F}_{S1}(a) = \begin{cases} e^{-\gamma a} & , a \in (0, \tau] \\ \frac{e^{-(\gamma+\lambda F(\tau))a}}{\frac{\lambda F(\tau)}{\gamma+\lambda F(\tau)} e^{-(\gamma+\lambda F(\tau))a} + \mathbf{c}} & , a \in (\tau, \infty] \end{cases} \quad (8)$$

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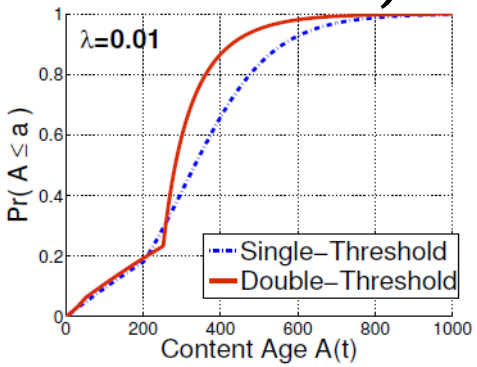
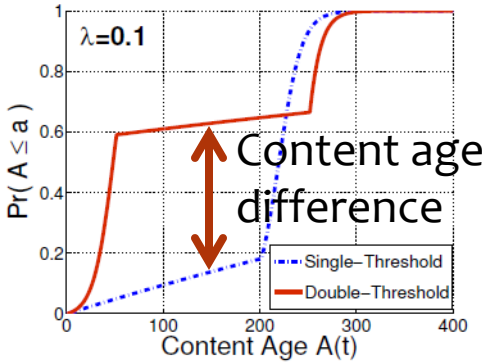
The content age distribution under two threshold device sleep/awake

Numerical Results

- Under energy normalization, we plot the content age distribution of analytical solutions in CDF form.
- Case1) User contact rate



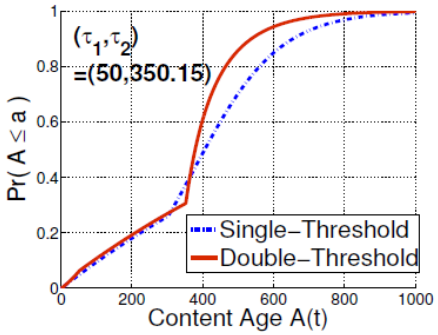
(a) Low User Contact Rate



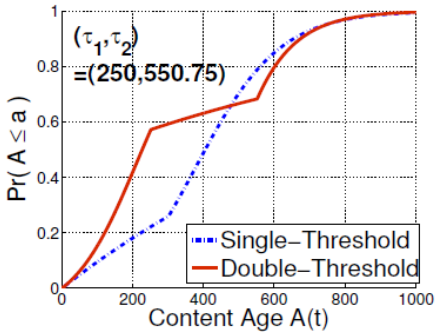
(b) High User Contact Rate

- User contact rate (λ) ↑ induces:
- The better freshness improvement of two-threshold sleep/awake rule.

- Case2) Different Energy Normalization Tuples for τ^*



(c) $(\tau_1, \tau_2) = (50, 350.15)$



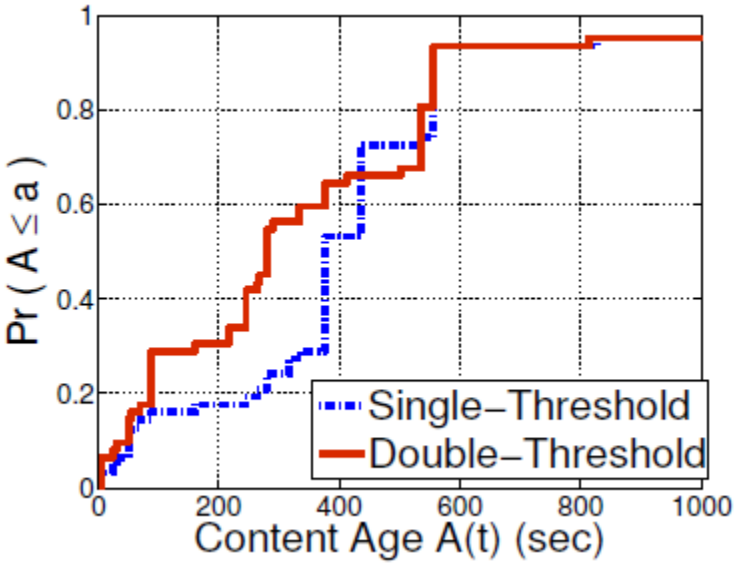
(d) $(\tau_1, \tau_2) = (250, 550.75)$

- For a given τ^* (for one-threshold sleep/awake):
- Several energy-normalized (τ_1, τ_2) tuples exists.
- Freshness performance is also affected by the tuple selection .

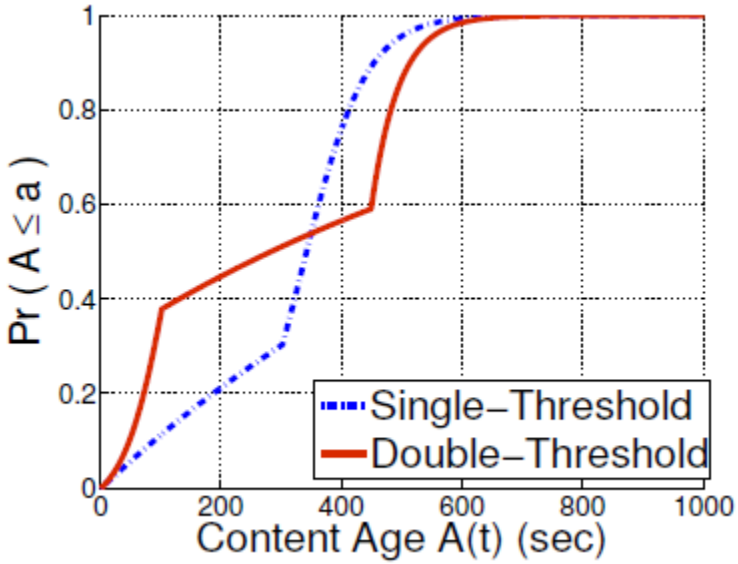
Trace-Based Tests

- Validate our analysis under the heterogeneity of users
- Roller-Net Trace (infocom09)
  - 63 i-Mote contact information in Paris roller-blade tour
  - High user contact rate (λ) and enough user heterogeneity

1) Distribution similarity of user content age



Roller-Net Trace Results

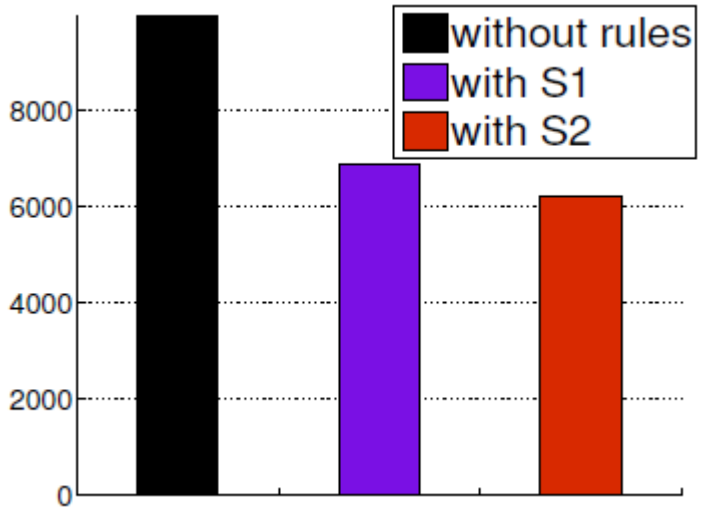


Our Analytical Solution

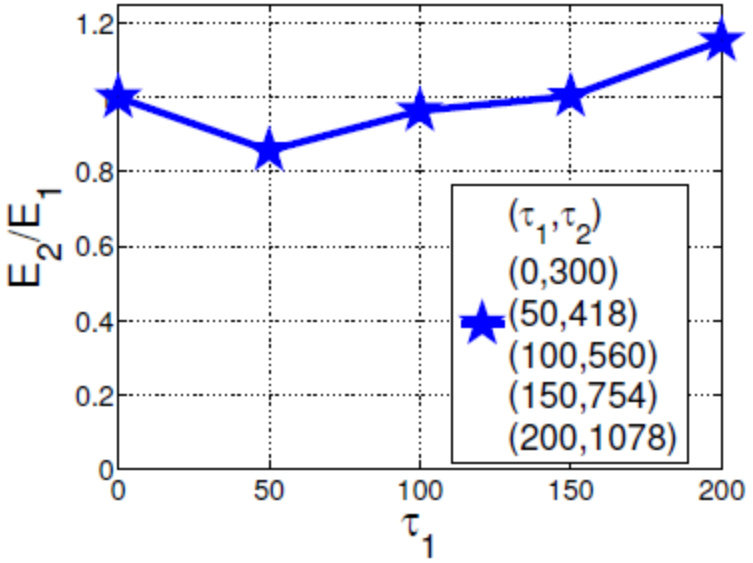
Trace-Based Tests (Cont')

2) Energy Normalization

Mean Energy Consumption of Devices



Mean Energy Consumption Ratio for Several Energy-normalized tuples (τ_1, τ_2)



$\tau^* = 300, (\tau_1, \tau_2) = (100, 447.36)$

- S1: One-Threshold sleep/awake
- S2: Two-Threshold sleep/awake
- Even under heterogeneous trace, the energy difference is 5.42%

- For given threshold τ^*, there exist several energy normalized tuples (τ_1, τ_2).
- Plot the energy consumption ratio for each case.
- Observe the effectiveness of our energy-normalization method

Summary

- We analyze the quantified performance changes of content update process under energy-saving rules.
  - The content category is time-sensitive
    - The content importance decreases with time (e.g., news, tweets)
  - Mobile-devices use sleep/awake rules
    - Due to energy-constraint
    - Two sleep/awake rule based on content freshness (i.e., age)
- From mean-field regime, we derived ODEs for content age-variation
- For different sleep/awake rules, we support an energy-normalization method (for fair comparison)
- Throughout real-trace based tests, we validated our analysis