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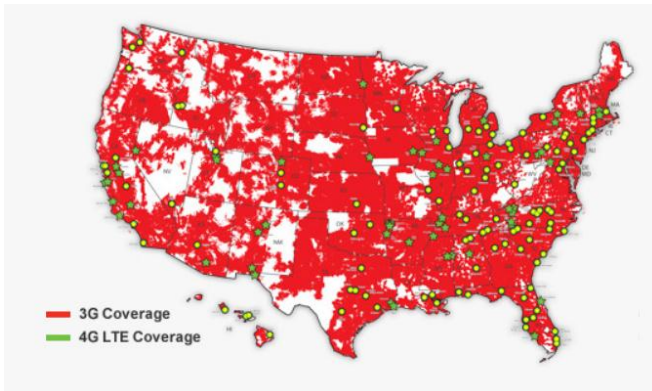


A Content-Freshness Enhancement with Infrastructures in Mobile Opportunistic Networks

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Gap between DTNs and Real Networks

- Assumption in DTN :
 - Network **connectivity** is **not always guaranteed**
- ‘**Contacts**’ among users become important
 - Why? Provide **an opportunity to forward contents**
- Current network situations in reality:



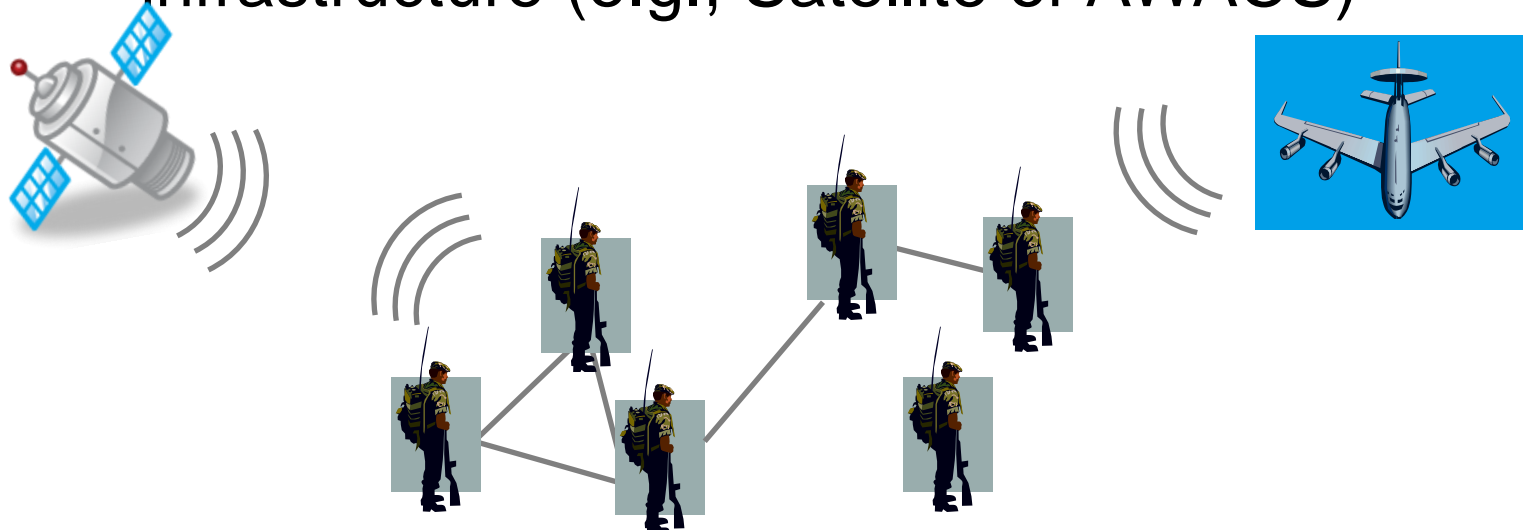
Network Coverage from Verizon



Military Operation in Saudi Arabia

Gap between DTNs and Real Networks

- Military operation **under no infrastructure**
 - Communication depends on **ad-hoc networks**
 - **New technologies** can support the role of infrastructure (e.g., Satellite or AWACS)



Challenging point:

“Measuring the degree of performance improvement (i.e., quantifying)”

Content freshness

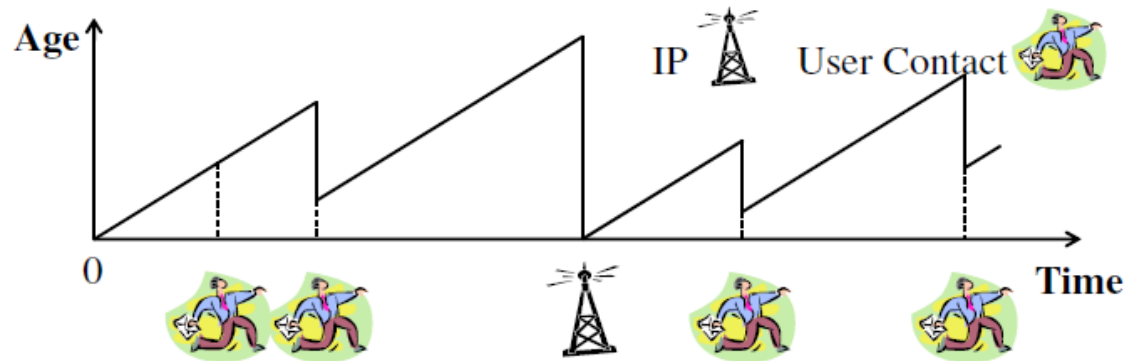
- Depending on content category, the importance of content can be affected by time
 - e.g.) News, Tweets, Military Commands, ...
 - We define them as ‘Time-sensitive content’ and consider its propagation process.

“Simply speaking, how fresh content can be obtained by users in the network.”

- To compare the freshness of contents:
 - We define a content age $A_i(t)$
 - At time t , user i 's content is generated $A_i(t)$ time age.

Content Update Process

- Content update process:** When a contact occurs between users, they compare their content-age and share the lesser of the two (i.e., $\min\{A_i(t), A_j(t)\}$).



(a) Content Update Process

- Analyzed by Chaintreau et al (SIGMETRICS09), Altman et al (Infocom09), Ioannidis et al (Infocom09)
- Still, information propagation only depends on “Opportunistic contacts among users”

Device Constraint

- **Communication Method Limitations:**
 - Not all users utilize the infrastructure freely
 - E.g.) Device Size (portability), Device Price, ...

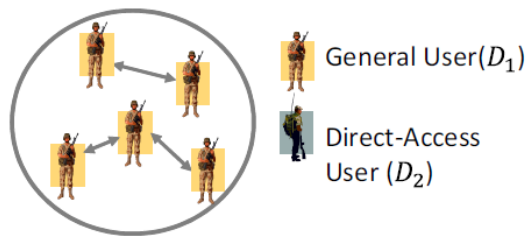


- **Energy Limitation of Mobile Devices:**
 - Due to battery operations
 - Long distance communication consumes the more energy

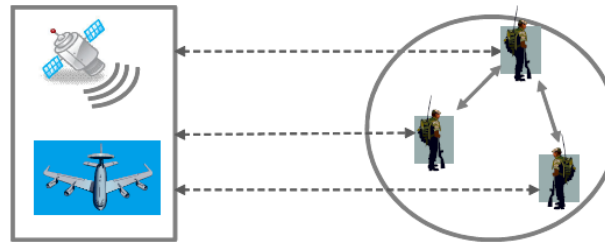
Propose *update rules for users* with considering above constraints

The Content Update Rule of Users

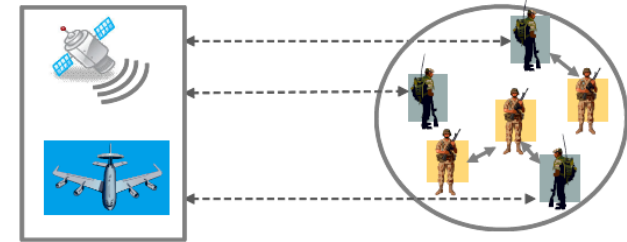
- **5 update rules** (rule $S_1 \sim S_5$, 3 broad categories)
- **Device differentiation:**
 - D_1 (ad-hoc communication only), D_2 (Infrastructure accessible)



(a) Opportunistic Contact Only (S_1)



(b) Direct-Update by All Users (S_2 and S_3)



(c) Direct-Update by Partial Number of Users (S_4 and S_5)

- **Ad-Hoc Network (S_1): D_1 only**
- **For performance comparisons with infrastructure-use networks**

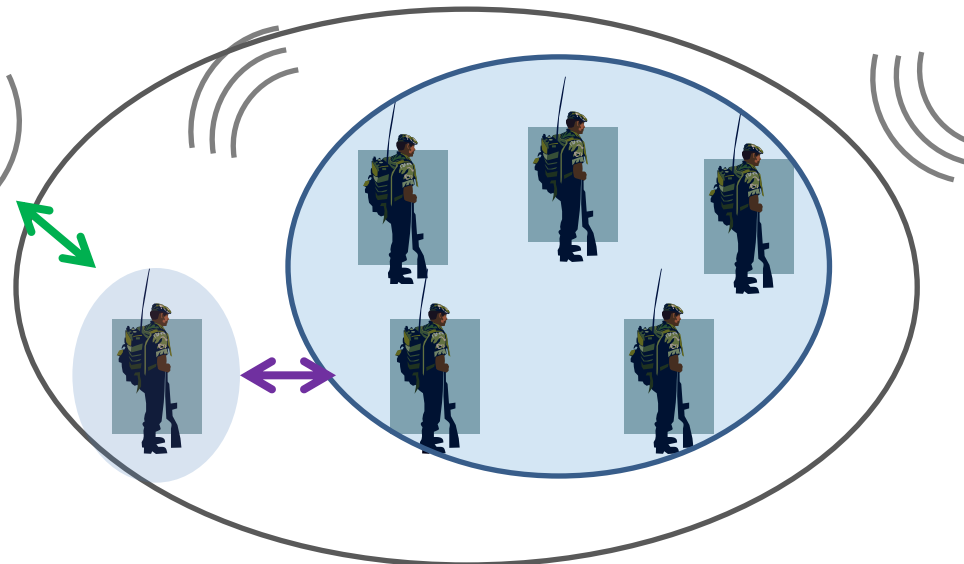
- **All users are infrastructure accessible: D_2 only**
- **Access Rate Control**
 - **Threshold-Based (S_2)**
 - **Age-Based (S_3)**

- **Mixed devices: $D_1 + D_2$**
- **Partial number of users utilize an infrastructure**
 - **Base-Station Update (S_4)**
 - **Sub-Leader Update (S_5)**

Network Conditions

- Network Parameters

Assume n mobile users and 1 IP



User and IP:

- Follow the previous user update rules

Between Users:

- Inter-Any-Contact with Rate λ
- Contact pair occurs Uniform-Randomly

Network Modeling

- Investigate the probability distribution of content-age (i.e., freshness) that users obtain
- How we get the age distribution of users?
 - **Inter-action among users + Infrastructure-based update**
 - Define $F_i(t, a)$: Probability that a user i has the larger content age than a at time t (i.e., $F_i(t, a) \equiv P(A_i(t) > a)$)
 - ODE construction:

$$\frac{d\mathbf{F}(t, a)}{dt} + \frac{d\mathbf{F}(t, a)}{da} = \lim_{\epsilon \rightarrow 0} \frac{\mathbf{F}(t + \epsilon, a) - \mathbf{F}(t, a - \epsilon)}{\epsilon}$$

- The content age distribution in steady-state (i.e., $t \rightarrow \infty$)
- During ϵ , the dynamics depends on user update rules

General Content-Age Dynamics

- For a user i :

$$A_i(t + \epsilon) = \begin{cases} \epsilon & \text{under condition 1} \\ \min\{A_i(t), A_j(t)\} + \epsilon & \text{under condition 2} \\ A_i(t) + \epsilon & \text{otherwise} \end{cases}$$

- *Conditions 1 and 2 vary according to update rules*
- Compute a conditional expectation for $F_i(t + \epsilon, a)$:

$$\mathbf{F}_i(t + \epsilon, a) = \mathbf{E}[\mathbf{F}_i(t + \epsilon, a) | A_i(t)]$$

- Induce an ODE form such that:

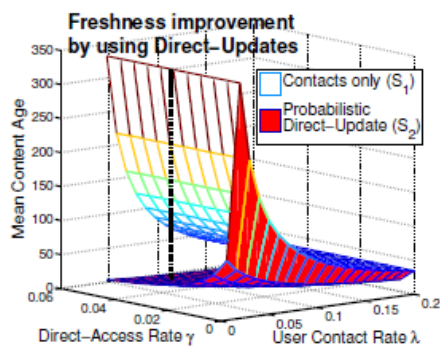
$$F_i'(a) = F_i(a) + \dots F_i(a)F_j(a) + \dots$$

- How to solve?
 - Assume *symmetric inter-actions* and *asymptotic independence* among users (Le Boudec [14], Chaintreau [9])

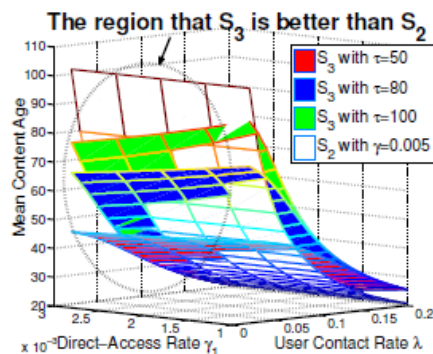
Analytical Results

- Closed-form CCDF $F(a)$: User content-age distribution
- Simple metric
 - Mean Content Age: convenient as $E[A] = \int_0^\infty P(A > a) da$

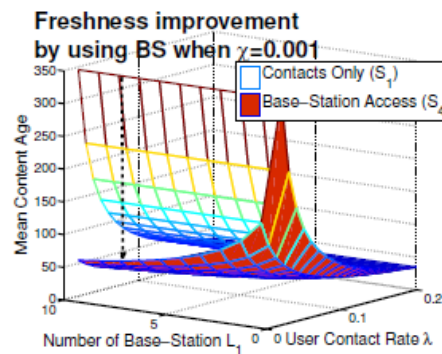
Update Rule	CCDF $F(a)$	Mean Content Age
S_1	<div style="border: 2px solid blue; border-radius: 15px; padding: 10px; display: inline-block;"> Allows the comparison of <i>quantified</i> freshness improvement that comes from infrastructure uses. </div>	$\frac{N}{\lambda(N-1)} \ln N$
S_2		$\frac{N}{\lambda(N-1)} \ln\left(\frac{N\gamma + \lambda N}{N\gamma + \lambda}\right)$
S_3		$\frac{N}{\lambda(N-1)} \ln\left(\frac{N(\lambda + \gamma_1)}{(N-1)\lambda e^{-(\lambda + \gamma_1)\tau} + N\gamma_1 + \lambda}\right) \frac{(N-1)\lambda e^{-(\lambda + \gamma_2)\tau} + C}{C}$
S_4		$\frac{N}{\lambda(N-1)} \ln\left(\frac{NL_1\chi + \lambda N}{NL_1\chi + \lambda}\right)$
S_5		$\frac{N}{\lambda(N-1-L_2)} \ln \frac{N}{1+L_2}$



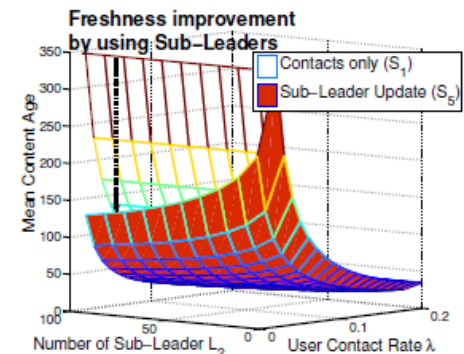
(a) Probabilistic Direct-Update (S_2)



(b) Age-Based Direct-Update (S_3)



(c) Base-Station Update (S_4)



(d) Sub-Leader Update (S_5)



Trace Results

- The necessity of trace-based tests:

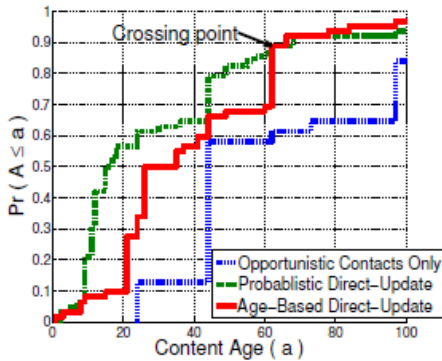
Our analysis assumed:

Symmetric interactions and asymptotic independence among users

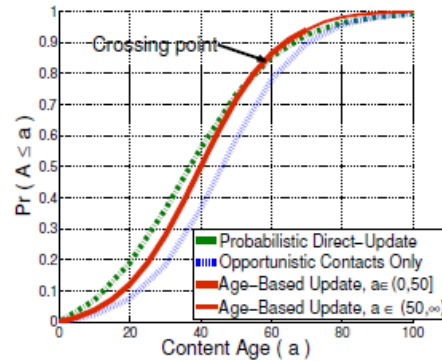
In Reality: User behaviors are *heterogeneous* (i.e., $\lambda_i \neq \lambda_j$)

- **Roller-Net Trace** [15] (Infocom 09)
 - 62 i-motes traces on Paris roller-blade tour for 3 hours
 - Grouping behavior (close to movements of troop)
 - Contact rate among users is highly heterogeneous

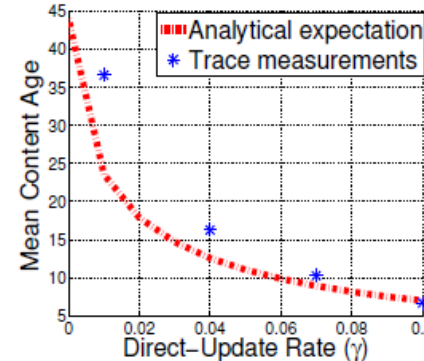
Distribution and Mean Comparisons



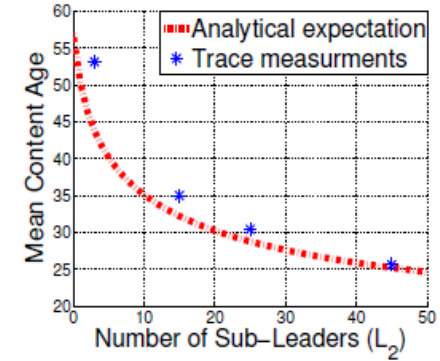
(a) Age-Distribution from Traces



(b) Analytical Age-Distribution



(c) Freshness Comparison under S_2



(d) Freshness Comparison under S_5

Content-Age Distribution of users for rules $S_1 \sim S_3$

- The freshness improvement trends:
 - Observe *the age-distribution bias* to early age a under infrastructure uses
 - The *trade-off between different update rules*

Mean-Content Age for rules S_4 and S_5

- The *convenience* of mean comparisons
- Quantify* the degree of freshness improvement for users
- Observe *the closeness of analytical solutions*

Conclusion

- Hybrid-Network Condition

- The *gap* between DTN researches and real networks
- *Opportunistic-based update + Infrastructures*

- Content-Freshness of Mobile Users

- '*Time – sensitive*' contents (e.g., news, tweets, military operations)
- Content Update Process with infrastructures

- Device Constraints

- *Functionality* differences
- *Energy limitation* of mobile devices

• Model & Test

- *ODE models* from Mean-Field based analysis
- Inter-acting among users (assumptions)
 - Symmetric inter-actions and asymptotic independence
- Trace-based validation (Roller-Net Traces)



Quantify the content-freshness degree of users
when infrastructures are combined into networks

Thank you