Density-Aware Routing in Disruption Tolerant Networks

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Delay-Tolerant Networking (DTN)

- **Delay-tolerant networking (DTN)** is an approach to computer network architecture that seeks to address technical issues in heterogeneous networks that are characterized by tight resource constraints on intermittent connectivity, available storage, and internode bandwidth throughput.
  - Delay/Disruptions may happen because of the limited wireless radio range, sparsity of mobile nodes, energy resources, attack, and communication noise.

In 2002, the term **delay-tolerant networking (DTN)** was coined. [Kevin Fall, Vint Cerf, et al.]

*Classical* examples of such networks are those operating in *mobile* or *extreme terrestrial* environments, or *planned* networks in space. *Recent* works on DTNs bring growing interest in combining works from *Sensor Networks* and *MANETs*. 
DTN Environments & Applications

- Interplanetary Internet, which focused primarily on deep-space communications in high delay environments
- Sensor-based networks, using scheduled intermittent connectivity
- Terrestrial wireless networks cannot ordinarily maintain end-to-end connectivity
- Satellite networks with moderate delays and periodic connectivity
- Underwater acoustic networks with moderate delays and frequent interruptions due to environmental factors

- Interplanetary space
- Natural disasters
- Agricultural lands
- Fishery grounds
- Forest parks
- Grazing areas
- Wilderness

Fukushima, One Year After
莫拉克颱風災情地圖

從過去幾次經驗，面對災害發生時，透過民衆提供的訊息往往比政府政務部門更及時，此次莫拉克颱風帶來驚人的能量，讓台灣各地發生重大災情。網友們耳聞目睹地透過Google地圖標示出各地即時的災情，也希望大家可以對災區投注必要的關心與支援。

- Google莫拉克颱風災情地圖
- 莫拉克颱風災情地圖 [ht.ly/KKvYh]
- 莫拉克災情資訊網（Credit: GemVГ Blog）
Delay-Tolerant Routing: Why

- Existing Internet routing and messaging mechanisms do not work well for DTNs due to several fundamental assumptions:
  - An end-to-end path between source and destination exists for the duration of a communication session. [y/n?]
  - Retransmissions based on timely and stable feedback from data receivers is an effective means for repairing transmission errors. [y/n?]
  - End-to-end loss is relatively small. [y/n?]
  - All routers and end stations support the TCP/IP protocols. [y/n?]
  - Selecting a single route between sender and receiver is sufficient. [y/n?]

Did you ever get false answers in mind?

Delay-tolerant routing may be one of important alternatives to resolve the issues.
Delay-Tolerant Routing in DTNs

- In DTNs, instantaneous end-to-end paths are difficult or impossible to be established and guaranteed
  - Due to the lack of network connectivity by many realistic constraints: intervening objects, sparse node densities, limited radio range, limited energy resource, and node mobility

- Popular ad hoc routing protocols, such as ad-hoc on-demand distance vector (AODV) and dynamic source routing (DSR), may fail to establish routes in these challenging environments.
  - These protocols try to first establish a complete route and then, after the route has been established, forward the data.
Delay-Tolerant Routing in DTNs

- Routing protocols can take to a *store, carry and forward* approach.
  - Data are sent to intermediate (relay) nodes where store and send data later over multiple paths to final destinations or to other relay nodes.
Delay-Tolerant Routing in DTNs

- Two major performance problems in DTNs
  - Long transfer delay time
  - Low message delivery ratio

- Replicating many copies of the message is a common technique used to maximize the probability of a message being successfully received.

- A more discriminating algorithm is required, however, when available storage and internode throughput opportunities are more tightly constrained.
Existing DTN Routing Protocols

- **Replica-based protocols** are feasible only when the networks can provide large amounts of local storage and internode bandwidth relative to expected message traffic and resource waste.

- **History-based protocols** require nodes to extra maintain a history of frequency with ever-encountered nodes, complicating the forwarding decision and inducing considerable computation and maintenance costs when node population is large.

- **Location-based protocols** were based on a weak premise that all nodes have special localization abilities, e.g., GPS.

- **Coding-based protocols** much concentrate on special coding technologies, e.g., erasure coding and network coding, rather than developing any routing algorithm itself in DTNs.
## Existing DTN Routing Protocols

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Density-Aware Routing Protocol

- We intend to exploits the natural characteristics of node density in proximity for the proposal of a new delay-tolerant routing scheme in DTNs.

- Non-uniform node distribution in the geographic scale, as well as in the timescale.
  
  - The distribution of node population has sparse and dense phenomena in many problem spaces.
    
    - For example, node density in an urban area is higher than that in a suburban area.
    
    - The node density in an urban area is higher during the office time than that at midnight.
    
    - In vehicular ad hoc networks, node density near crossroads is higher relatively.
Density-Aware Routing Protocol

● The idea is that nodes in DTNs should move or copy messages to encountered nodes that are going into dense areas because the inter-meeting time between two consecutive encounters in dense areas is shorter than that in sparse areas.

● Hopefully, nodes may be able to distribute messages rapidly in DTNs, reducing the transfer delay and increasing the message delivery ratio.

⇒ A new density-aware routing protocol
Literature Review on Density-Aware Routing

- Using different density concepts
  - Node density [a]
  - Replication density [b]
  - Map-based density [c]
  - Information density [d]
Density-Aware Routing with Node Density

- This work traced real message traffic produced by people wearing in-line skates during city tour activities.
- This work analyzed the accordion phenomenon of node distribution in DTNs, and proposed a modified SnW protocol where the number of distributed messages is proportional to the number of neighboring nodes in the vicinity.

Density-Aware Routing with Replication Density

- Replication density indicates that the ratio of the number of encountered nodes that already have the particular message by the total of encountered nodes within a time period.

- This work changed the replication policy in the epidemic routing protocol.
  - When a node determines that the current replication density is higher than a threshold, it will lower the probability of copying messages to neighboring nodes to reduce traffic load in the same area.

Density-Aware Routing with Map-based Density

- This work assumed that all nodes have GPS facilities and use location-aided knowledge to route messages in DTNs.
- Mobile nodes can mark the dense areas on the geographic map, and then forward query messages towards dense areas to receive fast responses.

Density-Aware Routing with Info. Density

- This work addressed the content retrieval based on information density in semantic DTN environments.
- Each node can overhear the content of any passing messages to learn semantic distances to the source and destination nodes in DTNs.
- Accordingly, a node can direct query message towards the area with higher information density to reduce the traffic by query messages.

Proposed Density-Aware Routing Protocol

- Linear Scheme
- Tree-based Scheme
Outline

- Introduction
- DTN Context Model
- **Density Aware Routing Protocol**
  - Inter-Meeting Time Normalization
  - Density Estimation
  - Boundary Detection
  - Forwarding Strategy
- Performance Results
- Conclusion
Density-Aware Routing Protocol

- The distribution of node population is non-uniform (sparse/dense) in the geographic scale, and time scale.
- In DTNs, *ideally*, nodes should move or copy messages to encountered nodes that are going into dense areas.
  - The inter-meeting time between two consecutive encounters in dense areas is shorter than that in sparse areas
  - Nodes may distribute messages rapidly in DTNs, hopefully reducing transfer delay and increasing message delivery ratio.
Our idea stems from …

- Keeping messages in the dense area
  - Considering non-uniform node distributions, it has higher probability to encounter target nodes with lower delay time.

- Generating a small, fixed number of message copies
  - Avoiding congestion and resource waste, where available storage and inter-node throughput opportunities are more tightly constrained

- Without auxiliary equipment (e.g. GPS)

- Exploiting the tendency of Inter-Meeting-Time
  - Good scalability (The factor is independent of node population)
  - Low complexity
DTN Context

- Two general assumptions
  - Nodes can be aware of their motion speeds
  - Each node can keep track of its Inter-Meeting-Time ($I$) with any encountered node
Density-Aware Routing Scheme

- Four phases
  1. Inter-meeting time normalization
  2. Density estimation
  3. Boundary detection
  4. Message forwarding
(1) Inter-Meeting Time Formulation

- **Design Properties:**
  - Each node $N_n$ estimates its local density with $I_n^i$.
  - With respect to any encountered nodes $N_1, N_2, N_3$ at time $t_1, t_2$, each node can have a sequence of $I = I_n^1, I_n^2, I_n^3, \ldots$.

  ![Inter-Meeting Time Diagram](image)

- **Node $N_n$ estimates its local density with $I_n^i$.**
  - At $t_1$, $N_n$ encounters a node and updates $\bar{I}_n^\alpha = \left(\sum_{k=1}^{\alpha} I_n^k\right) / \alpha$
    where $\alpha$ is the number of the preceding $I$s.
  - At $t_0$ and $I_n^0 \geq \bar{I}_n$, $N_n$ immediately updates $i_n^\alpha = \left(\sum_{k=0}^{\alpha-1} I_n^k\right) / \alpha$. 
Normalized Inter-Meeting Time

- In the Random WayPoint (RWP) Mobility model, the expectation of $I$ is in inverse proportion to a node’s motion speed $v$ [8].

$$E[I]_{rwp} = \frac{1}{p_m \hat{v}_{rwp} + 2(1 - p_m) \frac{A}{2RL}} \left(\bar{T} + \bar{T}_{stop}\right)$$

- $A$: size of network area
- $R$: transmission range
- $\bar{L}$: expected epoch distance
- $\bar{T}$: expected epoch duration
- $\bar{T}_{stop}$: average pause time after an epoch
- $\hat{v}_{rwp}$: normalized relative speed
Normalized Inter-Meeting Time

- With the simple simulation, the expectation of $I$ is in inverse proportion to a node’s motion speed $v$.
- Normalized $I$: $I = \hat{I} \cdot \frac{V}{V}$

$$E[I]_{rwp} = \frac{1}{p_m \bar{v}_{rwp} + 2(1-p_m)} \cdot \frac{A}{2RL} \left( \bar{T} + \bar{T}_{stop} \right), \quad (3)$$

where $\bar{T}$ is the mean time duration of each movement, $\bar{T}_{stop}$ is the average pause time after each movement, $A$ is the size of network area, $R$ is the transmission range, $\bar{L}$ is the average distance between two positions, $\bar{v}_{rwp} \approx 1.75$ is a normalized relative speed for RWP, and $p_m = \frac{\bar{T}}{\bar{T} + \bar{T}_{stop}}$ is the probability that a node is moving at any time. Given with $\bar{T}_{stop} = c \times \bar{T}$ and $p_m = \frac{1}{1+c}$ with a constant $c$, the above formula can be rewritten as

$$E[I]_{rwp} = \left( \frac{1}{p_m (\bar{v}_{rwp} - 2) + 2} \cdot \frac{(1+c)A}{2R} \right) \frac{\bar{T}}{\bar{L}} = K \frac{1}{V}, \quad (4)$$

where $K$ is a constant.
(2) Line-Based Density Estimation

- Define the density estimation $D_n(t)$ in $[0 \sim 0.5 \sim 1]$ as:

$$D_n(t) = \begin{cases} 
0 & , \quad \overline{I}_n^\alpha > 2\overline{I}_n \quad \text{and} \quad I_n^0 < \overline{I}_n \\
1 - \frac{\overline{I}_n^\alpha}{2\overline{I}_n} & , \quad \overline{I}_n^\alpha \leq 2\overline{I}_n \quad \text{and} \quad I_n^0 < \overline{I}_n \\
0 & , \quad \dot{I}_n^\alpha > 2\overline{I}_n \quad \text{and} \quad I_n^0 \geq \overline{I}_n \\
1 - \frac{\dot{I}_n^\alpha}{2\overline{I}_n} & , \quad \dot{I}_n^\alpha \leq 2\overline{I}_n \quad \text{and} \quad I_n^0 \geq \overline{I}_n
\end{cases}$$
Line-Based Density Estimation

- Two encountered nodes exchange their values of density estimate, i.e., $D_n(t)$ and $D_e(t)$
- For simplification, a node $N_n$ defines the real density estimate $\overline{D}_n(t)$ in $[0,1]$, given as

$$\overline{D}_n(t) = \frac{(D_n(t) + D_e(t))}{2}$$

similar $D_n(t)$

different $D_n(t)$
Line-Based Density Estimation

- Consider the factor of mobile trajectory for developing an incremental density estimation to enhance the estimation measure.
- The estimation incorporation can allow a node to obtain more estimation information from encountered nodes in the surrounding area of the current location to enhance its estimation of node density in the current area.
Tree-Based Density Estimation

- Keep track of $\sum_{i=1}^{\alpha} 2^i I$ instead of only considering $\alpha I$.
- Two encountered nodes exchange their values of density estimate, i.e., $D_n(t)$ and $D_e(t)$.
Tree-Based Density Estimation

- Building the tree based on the history table.
Tree-Based Density Estimation

- Local density estimation:

\[
\bar{I}_n^\alpha = \left( \sum_{k=1}^{\alpha} I_n^k \right)/\alpha
\]

\[
\bar{I}_n^\alpha = \left( \sum_{k=1}^{\alpha} \sum_{j=1}^{2^{\alpha-1}} 2^{-(\alpha-1)} I_{n,k,j} \right)/\alpha
\]

Weighting: \(2^{-(i-1)}\)

- Diagram showing the local density estimation process with various intervals and weighting factors.
Tree-Based Density Estimation

- Considering the encountered angle.
  - We try to know the quantity of information from the encountered node.

\[
D_n(t) = \left( D_n(t) + \sin \frac{\theta}{2} \times D_{\text{encounter node}}(t) \right) \div (1 + \sin \frac{\theta}{2})
\]
(3) Boundary Detection

- Two nodes determine that they should locate in a dense area boundary as $D_n(t) > 0.5$ and $D_e(t) < 0.5$
- Four Cases as two nodes encounter in a dense area boundary:

![Diagram of dense to sparse and sparse to dense transitions]
(4) Forwarding Strategy

- Quota-based routing scheme
  - There are a fixed number of $M$ message copies distributed in the network.
  - Binary spray delivery
  - Forwarding phase

- Packet forwarding priority
  - Destination > Spray phase > Forwarding phase
Forwarding Strategy

- The message forwarding process includes two phases
  - Binary spray phase:
    - The source node of a message initially starts with a replication quota of $M$ message copies.
    - When any node (source or relay node) has more than one message copies and encounters another node with no copies, it hands over half of its message copies to the other.
  - Wait phase:
    - When a node is left with only one copy, it switches to the wait phase.
    - Whenever such a node meets another node, it performs a proactive forwarding decision according to the information of density estimation in proximity and boundary detection.
Performance Results

- Simulation environment
- Performance measures
  - Effective density estimation
  - Delivery ratio with different values of $P$ and $\alpha$
  - Delivery ratio in different number of dense areas
  - Delivery ratio in different number of nodes
  - Delivery ratio in different buffer size
  - Transmission overhead in different number of nodes
  - Delivery ratio in different number of copies
  - Delivery ratio in different speeds
  - Delivery ratio in different map sizes
Simulation Environment

- The ONE Simulator (Opportunistic Network Environment)
  - Simulation area: 2400*2000 m²
  - Number of nodes: 100~1000 (300)
  - Transmission rate: 250 KB/s
  - Transmission range: 10 m
  - Buffer size: 10 MB
  - Message generation period: 50 seconds
  - Message size: 50 KB
  - Time to Live (TTL): 9000 seconds
  - Number of copies per message: 8

- Extended Random WayPoint Mobility model
  - Regarding the center of the map as a dense area, a parameter $P$ indicates the probability of a node moving toward the dense area
  - $P$: 0.1~0.9
  - Motion speed: 0.5~2.5 m/sec
  - Pause times: 0 second
  - Number of preceding inter-meeting times: $\alpha = 1$~6

The simulator runs in 345600 seconds and sends out 5912 original packets in total.
Effective Density Estimation

- $P = 0.6$
Delivery Ratio (Line based) with Different Values of $P$ and $\alpha$

$p$: the probability of a node moving toward the dense area

$\alpha$: the number of the recent $Is$
Delivery Ratio (Tree based) with Different Values of $P$ and $\alpha$
Delivery Ratio in Different Number of Dense Areas

- $P = 0.6$
Delivery Ratio in Different Number of Nodes

![Graph showing delivery ratio in different numbers of nodes. The graph compares SnW, Line Based, and Tree Based methods. The delivery ratio increases with the number of nodes for all methods, with Tree Based performing slightly better than Line Based and SnW.]
Delivery Ratio in Different Buffer size
Transmission Overhead in Different Number of Nodes

![Graph showing transmission overhead vs number of nodes for SnW, Line Based, Tree Based, and Epidemic protocols.](Image)
Delivery Ratio in Different Number of Copies
Delivery Ratio in Different Speeds

![Graph showing delivery ratio in different speeds with lines for SnW, Line Based, and Tree Based.]
Delivery Ratio in Different Map Sizes

![Graph showing delivery ratio in different map sizes for SnW, Line Based, and Tree Based methods.](image)
Summary of Experimental Results

- Density estimation using DARS is more effective in the case of larger node population.
- Transmission overhead by DARS is extremely lower than the flooding-based routing method.
- DARS outperforms the SnW and Epidemic methods with the buffer size of 2-5 MB.
- DARS can further improve the delivery ratio of SnW by 8% (as $\alpha = 4$ and $P = 0.6$).
Conclusion

- The proposed DARS enables mobile nodes to estimate the local density and keep messages in dense areas, significantly increasing the delivery ratio in DTNs.
- This design generates only a small, fixed number of message copies to avoid congestion and resource waste.
- DARS is affected by the number of dense areas.
Future Works

- Extensive simulations will be conducted to compare DARS with a wider range of networking protocols.
  - Mobility models
    - RWP
    - Community
    - Range-based
    - Cluster-based

- We intend to exploit the potential of using social relationship among nodes to build social communities, and then, to better improve performance.
Open Issues Yet

- Bundle Protocol [RFC5050]

- Most of previous research efforts were dedicated to the performance regarding how to send one message from the source to the destination.

- Unicasting versus Multicasting in DTN

- In-network Intelligence

- The relationship with social community
Q&A

Thank you for your listening.

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