www.s2is.org
International Journal on Smart Sensing and Intelligent Systems
ISSN 1178-5608

ADAPTIVE SPRAY ROUTING FOR OPPORTUNISTIC NETWORKS

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Submitted: Aug. 02,2012 ***Accepted: Jan. 5, 2013*** ***Published: Feb. 20, 2013***

Abstract- opportunistic networks are sparse wireless networks where most of the time there is no

complete path from the source to the destination. Many applications require delay constrained routing mechanism which can provide acceptable and resilient service in the face of challenged environments. A class of adaptive spray mechanisms which aims to achieve the delay constraint with low cost in dynamic circumstances was proposed in this paper. Adaptive spray mechanisms use relay nodes to make spray decisions in order to apperceive the change of network conditions exquisitely. These protocols are least-cost delay-bounded routing protocols under specific spray mechanisms. Theoretic analyses of adaptive spray routings at aspects of routing cost, copy redundancy and expected delay were also given in this paper. Simulation results have shown that adaptive spray mechanisms exhibit prominent superiority in routing cost, adaptability and scalability. Adaptive spray mechanisms are a class of correct and efficient delay-bounded routings for opportunistic networks.

Index terms*:* opportunistic networks, spray routing, delay constraint; adaptive

I. INTRODUCTION

Opportunistic networks are sparse wireless networks where most of the time there is no complete path from the source to the destination [1]. The messages can be forwarded to the destination ultimately in the manner of asynchronous transmission which relies on the contact opportunities between nodes in opportunistic networks. This character of Opportunistic network can greatly extend the space-time metric of information collection and processing. Therefore, opportunistic network will be an important access technology especially for future ubiquitous computing.

Although the transmissions in opportunistic network often show large delay, it doesn’t mean that there is no necessary to implement quality assurance. In fact, there is no application which can tolerate very large delay. For examples, electronic notice in campus networks [2] and village networks[3], short-term weather information in large national parks[4] and data feedback in precision agriculture must be forwarded with specific delay. On the other hand, as the access networks, configuration and forecast for QoS are also necessary in order to provide acceptable service (such as e-mail) in opportunistic networks. Hence opportunistic networks must provide acceptable and resilient service in the face of challenged environments.

Routing is a core issue in opportunistic networks. There have been many routing protocols in recent years. Study has shown that flooding-based schemes such as Epidemic [5], MRP [6], and MV [7] have high probability of delivery and the least delay in theory, but they waste a lot of energy and suffer from severe contention. On the other hand, despite the single-copy routing protocols such as DTC [8], MobySpace [9], and CAR [10] are energy efficient, they always have large delay. Some restricted flooding or spray mechanisms disseminate a small number of message copies to potential relay nodes, and then each copy finds routing to the destination independently. These mechanisms can obtain the desired delay performance without a lot of resource consumptions.

Spray and Wait [11] is a multi-copy routing based on restricted flooding which tries to balance the delay and energy. Spray and Wait combines the speediness of epidemic routing with the simplicity and thriftiness of direct transmission. This mechanism “sprays” a number of copies into the network, and then “waits” till one of these nodes meets the destination. Spray phase can be implemented based on different strategies. Paper [11] proposed the binary spray which has the minimum expected delay among all spray based routing algorithms. But this source-defined spray strategy can not adapt to dynamic environments.

Spray and Focus [12] replaced the direct transmission in wait phase with utility-based single-copy strategy and proposed the utility transfer mechanism to disseminate the history contact information. Paper [13] was absorbed in utility-based spraying and proposed three potential utility functions: Last-Seen-First Spraying, Most-Mobile-First Spraying and Most-Social-First Spraying. Jindal proposed distance utility based spray strategy[14] which utilized dynamic programming to calculate the optimal relay node. In addition, theoretical analysis of expected delay in single-copy case and multi-copy case were proposed in [15,16] respectively.

All of the above-mentioned spray mechanisms assume that the decisions of the number of copies and the mode of spray are made by source node. Actually, it is very difficult to obtain accurate network parameters in many opportunistic networks especially the applications with time-varying network environment. For example, the regional and scale are not fixed in vehicle networks and ad hoc city paradigm. Considering the large delivery delay of opportunistic networks, the change of network environment during the period of routing can not be ignored. As a result, the decisions which made by source node were often unable to meet the delay target. Therefore, it is necessary to propose the adaptive spray mechanism which can be dynamically adjusted in accordance with network environment. An effective way is that the relay nodes are used to make decisions on depth spray independently. Obviously, the relay nodes have fresher knowledge of the networking conditions than the source nodes; therefore the estimations of the delivery delay are more accurate. In the previous study, we used similar ideas to design adaptive transition routing protocol [17] and on-demand path compression algorithm [18].

In this paper, we introduced a class of adaptive spray mechanisms in dynamic opportunistic network. Adaptive spray mechanisms use the relay nodes to make spray decisions in order to apperceive the change of network conditions exquisitely. Adaptive spray mechanisms are least-cost delay-bounded routing protocols under specific spray mechanisms. Theoretic analyses of adaptive spray routings were also given in this paper at aspects of routing cost, copy redundancy and expected delay. Simulation results have shown that adaptive spray mechanisms exhibit prominent superiority in routing cost, adaptability and scalability, and are a class of correct and efficient delay-bounded routing mechanisms in opportunistic networks.

In the next section we defined the concept and process of adaptive spray mechanisms. Section 3 presented the performance analysis of our mechanisms in terms of routing cost, copy redundancy and expected delay. Section 4, where the performances of all the strategies were compared with respect to average delivery delay and average transmissions per message delivered. Finally, Section 5 summarized the paper.

II. ADAPTIVE SPRAY ROUTING

In this section, we introduced three adaptive spray mechanisms: ASS (Adaptive Single-Seed Spray), ABS (Adaptive Binary Spray) and AMS (Adaptive Multiple-Seed Spray).

Like Spray&Wait, adaptive spray mechanisms suppose that all nodes move according to some stochastic mobility model, whose "meeting times" are approximately exponentially distributed or have an exponential tail with expected meeting time equal to *EMT* (see Definition 4). This assumption is acceptable since a number of popular mobility models like Random Walk [19], Random Waypoint [20] and Random Direction [21], as well as more realistic, synthetic models exhibit such (approximately) exponential encounter characteristics. Therefore, adaptive spray mechanisms can be applied to all these models.

We introduced some concept about adaptive spray routing here:

Definition 1 (Spray Depth, H): the layer number in spray tree. Let H=1 when a new packet is created.

Definition 2 (Routing Cost, C): the average transmissions for each message. ***Routing Cost*** is equivalent to the number of copies disseminated in spray routing mechanisms.

Definition 3 (Average copy redundancy, $\bar{\sigma}$***):*** the average ratio of the number of redundant copies divided by the minimum number of copies to satisfy the delay constraint.

Since the decisions of spraying are made in relay nodes in adaptive spray routing, the nodes at same Spray Depth will make same spraying decisions in probability when all nodes move according to IID manner. Therefore, the number of copies sprayed by adaptive spray routing will depend on Spray Depth in spray mechanism. It means adaptive spray mechanism may produce redundant copies. So it is necessary to introduce Average copy redundancy to evaluate the efficiency of adaptive spray mechanisms. Low Average copy redundancy means high spray efficiency and low routing cost in adaptive spray mechanisms.

Definition 4 (Expect Meeting Time, EMT): the expected time until two independent nodes which move according to some random mobility models, starting from the stationary distribution, first meet each other.

Denote E as the size of area, R as the transmission range of node, we can get formula (1) if all nodes move according to random walk models (The interested reader can find the proof in [15]):

$$EMT = 0.5E(0.34\log E - \frac{2^{R+1} - R - 2}{2^{R} - 1}) \tag{1}$$

It is necessary to note that *EMT* is estimated independently by each node in order to apperceive the network condition timely. Despite we can get *EMT* by formula (1) when the parameters are known, the estimation of *EMT* is also an efficient method when it is difficult to catch the parameters especially in dynamic networks. We adopted the estimation method proposed in [11] of which the details were omitted due to limitations of space.

Definition 5 (Seed): the qualification for forwarding message copies.

In traditional spray mechanism, all of the nodes which received more than one copies can spray further, while spray operation was only authorized in the nodes with seed(s) in ASS and AMS. Adaptive spray mechanism contains *spray phase* and *wait phase*, and the spraying decisions are made by *spray decision-making algorithm*. In addition, we add *H* (current depth of spray) and D_t (target delay) in the head of bundles [22] for ASS, ABS and AMS. Two extra fields *K* (the number of seeds) and K_{cur} (the number of seeds in current node) are also required in AMS.

Adaptive spray mechanisms aimed to achieve the delay constraint with low cost in dynamic circumstances. There are three metrics for evaluation: ①capacity of delay constraint, small expected delay of adaptive spray mechanism often means great capacity of delay constraint; ②*Routing Cost*, it is clear that less message copies means less transmissions and energy consumption; ③*Average copy redundancy*, it is used to evaluate the efficiency of adaptive spray mechanisms.

a. Adaptive Single-Seed Spray

Spray phase: the source node initializes only one seed. Each node *A* which received seed decides whether to create and forward a new copy to the next potential relay node *B* which does not have the same copy based on *spray decision-making algorithm*, and transfers seed to one of

A and *B*(according to some strategy such as utility evaluation of nodes). Repeat the process until node *A* makes sure that it is not necessary to create new copy or node *A* had encountered the destination *D*.

Wait phase: such node which received copy can only perform direct transmission if ①it is not a seed node or ②it makes sure that it is not necessary to spray new copy based on *spray decision-making algorithm*.

Spray decision-making algorithm: every node which received seed decides whether to create a new copy based on formula: $D_{cur} + D_{rw} < D_t$ (2)

where D_{cur} is the time had elapsed which can be derived from the time-stamp of packet, D_{rw} is estimated residual delay, and D_t is the target delay which derived from the head item in bundles. Furthermore, it is easy to deduce $D_{rw}=EMT/C_{ASS}$ according to *Definition 4* (C_{ASS} is the current routing cost of ASS which will given in *Theorem 3.1.1*). Seed node creates new copy until formula (2) is true.

The spray tree of ASS was depicted in Figure 1:

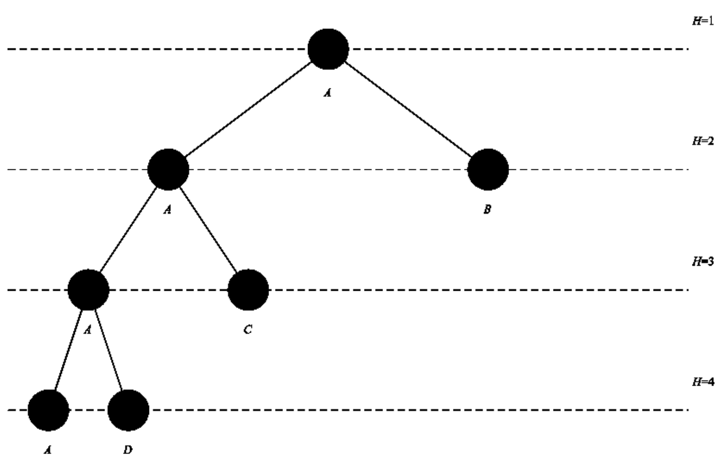


Figure1. Spray tree of ASS

b. Adaptive Binary Spray

Spray phase: each node *A* which received a message copy decides whether to create and forward a new copy to the next potential relay node *B* which does not have the same copy based on *spray decision-making algorithm*. Repeat the process until node *A* makes sure that it is not necessary to create new copy or node A had encountered the destination D.

Wait phase: the nodes which received copy can only perform direct transmission if it makes sure that it is not necessary to spray new copy based on *spray decision-making algorithm*.

Spray decision-making algorithm: every node which received copy decides whether to create a new copy based on formula (2). We can get $D_{rw}=EMT/C_{ABS}$ according to *Definition 4* (C_{ABS} is the current routing cost of ABS which will be given in *Theorem 2.2.1*). Such node creates new copy until formula (2) is true.

Theorem 2.2.1: When all nodes move in IID manner, ABS minimizes the expected time until all copies have been sprayed.

Proof: the nodes at same *Spray Depth* will make same spraying decisions and accomplish spraying at same time in probability when all nodes move according to IID manner. Therefore, the spray delay of ABS equal to the spray delay of binary spray&wait[11] whose spray tree is a full binary tree depicted in Figure 2. Since the nodes at same *Spray Depth* disseminate copies in a parallel manner, the spray delay of adaptive spray mechanism depends on the number of nodes which received copy at each *Spray Depth,* that is, the *Routing Cost* at current *Spray Depth.* According to the property of full binary tree, we can get $C_{ABS}=2^{H-1}$ which is maximum among all tree structure. It implies that ABS minimizes the expected time until all necessary copies have been sprayed. ♦

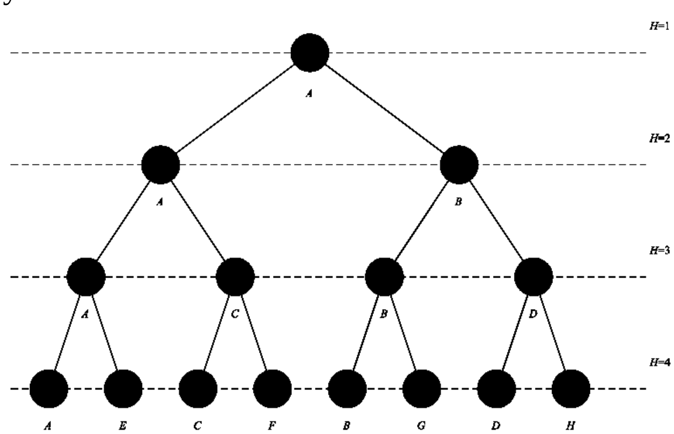


Figure2. Spray tree of ABS

c. Adaptive Multiple-Seed Spray

Spray phase: the source node initializes K seeds ($K \geq 1$, the calculation of K was given in section

3.3). Each node *A* which received seeds decides whether to create and forward a new copy to the next potential relay node *B* which does not have the same copy based on *spray decision-making algorithm*, and disseminates seeds in binary manner. Repeat the process until node *A* makes sure that it is not necessary to create new copy or node *A* has encountered the destination *D*.

Wait phase: same to the *Wait phase* of ASS.

Spray decision-making algorithm: every node which received seeds decides whether to create a new copy based on formula (2). We can get $D_{rw}=EMT/C_{AMS}$ according to *Definition 4* (C_{AMS} is the current routing cost of AMS which will given in *Theorem 3.1.1*). Such node creates new copy until formula (2) is true.

The spray tree of AMS with K=2 was depicted in Figure 3:

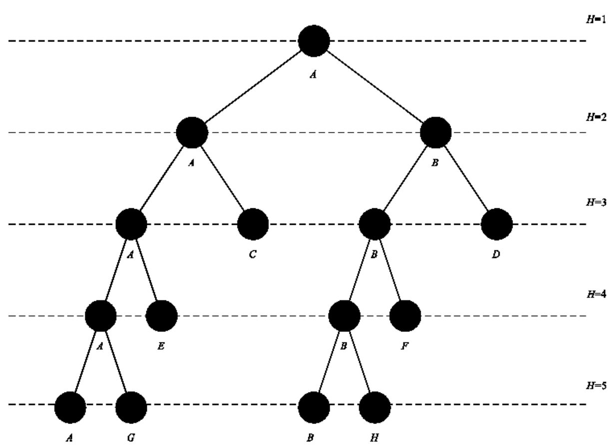


Figure3. Spray tree of AMS

III. PERFORMANCE ANALYSES

a. Routing Cost

Theorem 3.1.1 : Denote C_{ASS}、C_{ABS} and C_{AMS} as the routing cost of ASS、ABS and AMS, then:

$$
\begin{aligned}
&C_{ASS} = H \\
&C_{ABS} = 2^{H-1} \\
&C_{AMS} = \begin{cases} C_{AMS}(H) = 2^{H-1} & K \geq 2^{H-2} \\ C_{AMS}(H,K) = K(H - \lfloor \log K \rfloor - 1) + 2^{\lfloor \log K \rfloor} & K < 2^{H-2} \end{cases}
\end{aligned}
\tag{3}
$$

Where, H is the current spray depth, K is the number of seeds.

Proof: since ASS disseminates message copies in serial manner, only one seed node can spray at any time in the whole network; therefore the routing cost of ASS is equal to H. The routing cost of ABS has been given in theorem2.2.1. We focus on the routing cost of AMS here. There are two cases:

(1) $K \geq 2^{H-2}$, in this case, all nodes which received copy have seeds after spray depth H-1. Therefore, the number of children (nodes which received copy) at Hth layer is equal to the number of binary spray&wait, that is, 2^{H-1}.

(2) $K<2^{H-2}$, in this case, not all nodes which received copy have seeds after (H-1)th layer, AMS add K nodes at each layer after Hth layer. Therefore, The number of children after spray depth H is the sum of number of children at (H-1)th layer and the added nodes later. When the maximum of H which satisfies $K \geq 2^{H-2}$ is $\lfloor \log K+2 \rfloor$, the spray depth of H-1 is $\lfloor \log K+1 \rfloor$ and the number of children is $2^{\lfloor \log K+1 \rfloor - 1} = 2^{\lfloor \log K \rfloor}$. On the other hand, the added number of nodes is $K(H-\lfloor \log K+1 \rfloor) = K(H-\lfloor \log K \rfloor -1)$. So we have $C_{AMS} = K(H - \lfloor \log K \rfloor - 1) + 2^{\lfloor \log K \rfloor}$. ♦

Theorem 3.1.1 shows that ABS is a special case of AMS. When $K \geq 2^{H-2}$, ABS is equivalent to AMS of which the routing cost is independent of K.

b. Average Copy Redundancy

There is no redundant copy in ASS since only one seed node has the right to spray. So it is easy to get $\overline{\sigma}_{ASS} = 0$.

However, more than one node has the right to spray in ABS and AMS. These nodes have the same decisions of spraying in probability. On the other hand, it is not realistic to implement on-line consultation mechanism between nodes in opportunistic networks. So, any form of adaptive parallel spray will induce redundant copies. *Average copy redundancy* of ABS and AMS were given in *Theorem 3.2.1* and *Theorem 3.2.2*.

Theorem 3.2.1: Let H denote the current depth of spray, $\bar{\sigma}_{ABS}$ denotes the *Average copy redundancy* of ABS, then:

$$\bar{\sigma}_{ABS} = \begin{cases} 0 & H \le 2 \\ \dfrac{1/2 - 1/2^{H-1}}{3/2 + 1/2^{H-1}} & H > 2 \end{cases} \tag{4}$$

Proof: When $H \le 2$, only one copy was forwarded in ABS and $\bar{\sigma}_{ABS}=0$; When $H>2$, the total number of the copies which are forwarded is $L=2^{H-1}$ and the necessary number of copies is $L_c=2^{H-2}+i$ (i stands for the number of the necessary copies at last layer, $i=1,2,\ldots, 2^{H-2}$) . Hence we have $\bar{\sigma}_{ABS} = \dfrac{\sum_{i=1}^{2^{H-2}} (2^{H-1} - (2^{H-2}+i))}{\sum_{i=1}^{2^{H-2}} (2^{H-2}+i)}$. Suppose i is subjected to uniformity distribution with $\{1,2,\ldots, 2^{H-2}\}$, then $\bar{\sigma}_{ABS} = \dfrac{1/2 - 1/2^{H-1}}{3/2 + 1/2^{H-1}}$. ♦

Theorem 3.2.1 indicates that $\bar{\sigma}_{ABS}$ is an increasing function of H when $H>2$, and there is a maximum of $\bar{\sigma}_{ABS}$, $\bar{\sigma}_{ABS\_max} = 1/3$ when $H \to \infty$.

Theorem 3.2.2: Let H denote the current depth of spray, $\bar{\sigma}_{AMS}$ denotes *Average copy redundancy* of AMS with K seeds, then:

$$\bar{\sigma}_{AMS} = \begin{cases} \bar{\sigma}_{ABS} & K \ge 2^{H-2} \\ \dfrac{K-1}{2(2^{\lfloor \log K \rfloor + 1} + K(H - \lfloor \log K \rfloor - 3)) + K + 1} & K < 2^{H-2} \end{cases} \tag{5}$$

We omit the proof which is similar to that of *Theorem 3.2.1*. *Theorem 3.2.2* indicates that the *Average copy redundancy* of AMS is equal to that of ABS when $K \ge 2^{H-2}$. It also implies $\bar{\sigma}_{AMS}$ is an increasing function of K if $K<2^{H-2}$, and there is a minimum of $\bar{\sigma}_{AMS}$, $\bar{\sigma}_{AMS\_min} = 0$ when $K=1$, and $\bar{\sigma}_{AMS} \to \bar{\sigma}_{ABS}$ when $K \to 2^{H-2}$.

Now, we summarized the *Average copy redundancy*: ABS has the most copy redundancies; the *Average copy redundancy* of AMS is an increasing function of the number of seed; there is no *redundant copy* in ASS.

c. DELAY

The accurate delay expressions of ASS, ABS and AMS have been given in the following three theorems.

Theorem 3.3.1: Denote ED_{ASS} as the expected delay of ASS, and $ED(H)$ as the remaining time to accomplish ASS process. Obviously, $ED_{ASS}= ED(1)$. Suppose that there are M nodes in the whole network, and Nth layer spray is required to meet the target delay, then:

$$\begin{aligned} ED(H) &= \frac{EMT}{H(M-H)} + \frac{M-H-1}{M-H}\left(\frac{H-1}{H}ED(H) + \frac{1}{H}ED(H+1)\right) \\ ED(N) &= \frac{EMT}{N} \end{aligned} \tag{6}$$

Proof: according to the process of ASS, there are H nodes which received copy after Hth layer. Since all hitting times are independent and exponentially distributed, the time until any node A with a message copy encounters any node B without one (M-H) is equal to $\frac{EMT}{H(M-H)}$.

If B is the destination (with probability $\frac{1}{M-H}$), ASS process finished. Otherwise (with probability $1-\frac{1}{M-H}=\frac{M-H-1}{M-H}$), the algorithm continues, performing one of the following: (1) with probability $(H$-$1)/H$, A is not a seed node, and encountered a new node. Since these relays only forward their message copies to the destination, nothing happens, and the remaining time is still $ED(H)$; (2) with probability $1/H$, A is a seed node that encountered a new node without the same copy, and therefore it creates and hands a new copy. H+1 nodes have copy now, and an expected time $ED(H+1)$ remains until delivery.

When accomplished Nth spray, ASS carries out wait phase until any one of the nodes with a message copy encounters the destination D. It is clear that the time of wait phase is EMT/N according to *Definition 4*. Putting it together, we get the recursive equation (6). ♦

Theorem 3.3.2: Denote ED_{ABS} as the expected delay of ABS, and $ED(H)$ as the remaining time to accomplish ABS process. Obviously, $ED_{ABS}= ED(1)$. Suppose that there are M nodes in the whole network, and Nth layer spray is required to meet the target delay, then:

$$\begin{aligned} ED(H) &= \frac{EMT}{2^{H-1}(M-2^{H-1})} + \frac{M-2^{H-1}-1}{M-2^{H-1}}ED(H+1) \\ ED(N) &= \frac{EMT}{2^{N-1}} \end{aligned} \tag{7}$$

Proof: according to *Theorem 3.1.1*, there are 2^{H-1} nodes which received copy after Hth layer. Since all hitting times are independent and exponentially distributed, the time until any node A with a message copy encounters any node B without one (M-2^{H-1}) is equal to $\frac{EMT}{2^{H-1}(M-2^{H-1})}$.

If B is the destination (with probability $\frac{1}{M-2^{H-1}}$), ABS process finished. Otherwise (with probability $1-\frac{1}{M-2^{H-1}}=\frac{M-2^{H-1}-1}{M-2^{H-1}}$) the algorithm continues, performing (H+1)th layer spray, and the expected delay $ED(H+1)$ remains.

When accomplished Nth spray, ABS carries out wait phase until any one of the nodes which received copy encounters the destination D. It is clear that the time of wait phase is $EMT/2^{N-1}$ according to *Definition 4*. Putting it together, we get the recursive equation (7). ♦

Theorem 3.3.3: Denote ED_{AMS} as the expected delay of AMS, and $ED(H)$ as the remaining time to accomplish AMS process. Obviously, $ED_{AMS}= ED(1)$. Suppose that there are M nodes in the whole network. If Nth layer spray and K seeds are needed to meet the target delay, then:

$$
\begin{aligned}
ED(H) &= \frac{EMT}{C_{AMS}(H)(M-C_{AMS}(H))}+\frac{M-C_{AMS}(H)-1}{M-C_{AMS}(H)}ED(H+1) \quad K \ge 2^{H\text{-}2} \\
ED(H) &= \frac{EMT}{C_{AMS}(H,K)(M-C_{AMS}(H,K))}+\frac{M-C_{AMS}(H,K)-1}{M-C_{AMS}(H,K)} \\
&\quad \times \left(\frac{C_{AMS}(H,K)-K}{C_{AMS}(H,K)}ED(H)+\frac{K}{C_{AMS}(H,K)}ED(H+1)\right) \qquad K < 2^{H\text{-}2} \\
ED(N) &= \frac{EMT}{C_{AMS}(N)} \quad K \ge 2^{N\text{-}2} \\
ED(N) &= \frac{EMT}{C_{AMS}(N,K)} \quad K < 2^{N\text{-}2}
\end{aligned}
\tag{8}
$$

Proof: according to the process of AMS, there are C_{AMS} nodes which received copy after Hth layer. Further, let's suppose that, among the C_{AMS} nodes which have received copy, x of them have seeds, and they are allowed to forward copy further to other relays. Since all hitting times are independent and exponentially distributed, the time until any node A with a message copy encounters any node B without one (M-C_{AMS}) is equal to $\frac{EMT}{C_{AMS}(M-C_{AMS})}$.

If B is the destination (with probability $\frac{1}{M-C_{AMS}}$), AMS process finished. Otherwise (with probability $1-\frac{1}{M-C_{AMS}}=\frac{M-C_{AMS}-1}{M-C_{AMS}}$) the algorithm continues, performing one of the following:

(1) with probability (C_{AMS} -x)/C_{AMS}, A is not a seed node, and encountered a new node. Since these relays only forward their message copies to the destination, nothing happens, and the remaining time is still $ED(H)$; (2) with probability x/C_{AMS}, A is a seed node that encountered a new node without the same copy, performing (H+1)th layer spray, and the expected time $ED(H+1)$ remains.

When $K\geq 2^{H-2}$, all nodes which received copy are seed nodes, then $x=2^{H-1}$; when $K\geq 2^{H-2}$, $x=K$. Further, C_{AMS} was given in *Theorem 3.1.1* based on above-mentioned two cases. So we get the expression of $ED(H)$, that is, the expected spray delay of AMS process.

When Nth spray was accomplished, AMS carries out wait phase until any one of the nodes with a message copy encounters the destination D. It is clear that the time of wait phase is EMT/C_{AMS} according to *Definition 4*. Putting it together, we get the recursive equation (8). ♦

Theorem 3.3.3 shows that the expected delay of AMS is same as the expected delay of ABS when $K\geq 2^{H-2}$. This means AMS has the same delay constraint performance with ABS.

Despite the above-mentioned three theorems provided the accurate expression of adaptive spray mechanisms, it is not a closed form. This makes it difficult to calculate the expected delay of adaptive spray mechanisms, or to calculate the number of seeds and copies in closed form in order to meet performance constraints. For this reason, we also derived an upper bound of the expected delay of ASS, ABS and AMS in closed form in the following theorems

Theorem 3.3.4: The following upper bound holds for the expected delay of ASS:

$$ED_{ASS}\leq\sum_{H=1}^{N-1}\frac{EMT}{(M-H)}+\frac{M-N}{M-1}\frac{EMT}{N} \tag{9}$$

Where, N denotes the spray depth ($N \le M$).

Proof: Suppose that, the network area, network scale and transmission range are fixed, then each relay node will has equal probability to decide whether to create the copy (they have the same perception of network environment). So we can simplify the process of ASS to source spraying in which only the source node can decide the spray depth and disseminate the copy. The upper bound holds for the expected delay of source spraying had been given in [16]. ♦

Theorem 3.3.5: The following upper bound holds for the expected delay of ABS:

$$ED_{ABS} \le \sum_{H=1}^{N-1} \frac{EMT}{2^{H-1}(M-2^{H-1})} + \frac{(M-2^{N-1})}{(M-1)} \frac{EMT}{2^{N-1}} \tag{10}$$

Where, N denotes the spray depth ($2^{N-1} \le M$).

Proof: Suppose that, wait phase doesn't carry out in spray phase, and then the expected delay is the sum of expected spray delay and expected wait delay. According to *Theorem 3.1.1,* there are 2^{H-1} nodes which received copy when the current spray depth is H. This means the time until any one of the 2^{H-1} nodes disseminates copy to any one of M-2^{H-1} is equal to $\frac{EMT}{2^{H-1}(M-2^{H-1})}$.

The spray process will continue until Nth layer with total time $\sum_{H=1}^{N-1} \frac{EMT}{2^{H-1}(M-2^{H-1})}$, that is, the expected spray delay of ABS. If the destination is not among the 2^{N-1}-1 nodes which received copy, ABS will carry out wait phase with probability $1-\frac{2^{N-1}-1}{M-1}=\frac{M-2^{N-1}}{M-1}$. It is clear that the expected wait delay is $\frac{EMT}{2^{N-1}}$. Putting it together, we get the upper bound which holds for the expected delay of ABS since we assume wait phase does not carry out in spray phase. ♦

Theorem 3.3.6: The following upper bound holds for the expected delay of AMS:

(1) $K \ge 2^{N-2}$

$$ED_{AMS} \le \sum_{H=1}^{N-1} \frac{EMT}{C_{AMS}(H)\cdot(M-C_{AMS}(H))} + \frac{(M-C_{AMS}(N))}{(M-1)} \frac{EMT}{C_{AMS}(N)} \tag{11}$$

(2) $K < 2^{N-2}$

$$\begin{aligned} ED_{AMS} \le & \sum_{H=1}^{\lfloor \log K \rfloor + 2} \frac{EMT}{C_{AMS}(H)\cdot(M-C_{AMS}(H))} \\ & + \sum_{H=\lfloor \log K \rfloor + 3}^{N-1} \frac{EMT}{K(M-C_{AMS}(H,K))} + \frac{(M-C_{AMS}(N,K))}{(M-1)} \frac{EMT}{C_{AMS}(N,K)} \end{aligned} \tag{12}$$

Where, K is the number of seeds, N is the spray depth ($C_{AMS}(N) \leq M$ or $C_{AMS}(N,K) \leq M$).

Proof: Suppose that, wait phase doesn't carry out in spray phase, and then the expected delay is the sum of expected spray delay and expected wait delay. When $K \geq 2^{N-2}$, AMS is equivalent to ABS according to *Theorem 3.1.1* and then $ED_{AMS}=ED_{ABS}$.

When $K<2^{N-2}$, the spray delay of AMS contains two parts: (1) $K \geq 2^{H-2}$, the number of nodes which received copy is $C_{AMS}(H)$ at Hth layer, and the spray delay is $\frac{EMT}{C_{AMS}(H)\cdot(M-C_{AMS}(H))}$; (2) $K<2^{H-2}$, the number of nodes which received copy is $C_{AMS}(H,K)$ at Hth layer, and the time until any one of the K nodes disseminates copy to any one of M-$C_{AMS}(H,K)$ is equal to $\frac{EMT}{2^{H-1}(M-2^{H-1})}$. The spray process will continue until Nth layer, and we get the spray delay.

If the destination is not among the $C_{AMS}(N,K)$-1 nodes which received copy, AMS will carry out wait phase with probability $1-\frac{C_{AMS}(N,K)-1}{M-1}=\frac{M-C_{AMS}(N,K)}{M-1}$. It is clear that the expected wait delay is $\frac{EMT}{C_{AMS}(N,K)}$. Putting it together, we get the upper bound which holds for the expected delay of AMS since we assume wait phase doesn't carry out in spray phase. ♦

Figure 4 has shown the upper bound of expected delay of AMS with different N and K. We can see that the upper bound decreased with increasing K when N is fixed. *Theorem 3.1.1* has shown that the number of message copies is an increasing function of K. Therefore, the upper bound must decrease since more message copies are added to network.

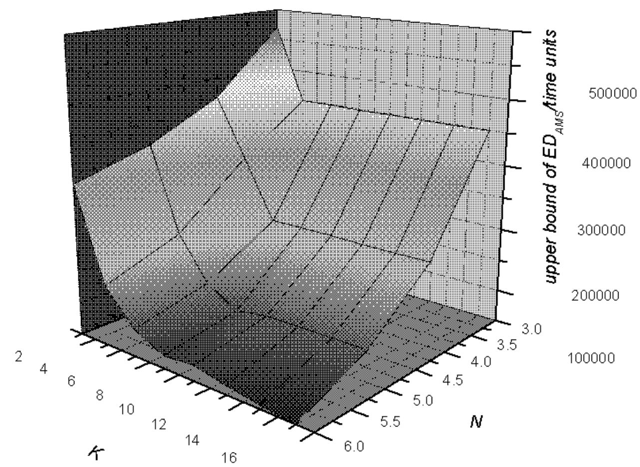


Figure4. The upper bound of ED_{AMS} calculated by *Theorem 3.3.6* with different K and N

So far, *Theorem 3.3.4-3.3.6* have provided the method to estimate the expected delay of our adaptive spray mechanisms. On the other hand, it is an efficient way to calculate the minimum of spray depth, seeds (for AMS) and corresponding routing cost to meet the target delay.

Suppose that, there are 100 nodes which move according to Random Walk model in area E=10^6 with transmission range R=10. Figure 5 has shown the routing cost of ASS, ABS and AMS to achieve the target delay. We can see that ASS can't satisfy the small target delay ($<25\times10^4$) due to the serial spraying which disseminates copies slowly. On the other hand, ASS outperforms all protocols in terms of routing cost since there is no copy redundancy in the whole spray process. ABS and AMS have small expected delay, and show prominent superiority in delay constraint performance. Furthermore, ABS performed more routing cost than ASS and AMS. Therefore, ASS is efficient in resource sensitive opportunistic networks with relaxed delay constraint. Oppositely, ABS and AMS are suitable for the case with strict performance constraint.

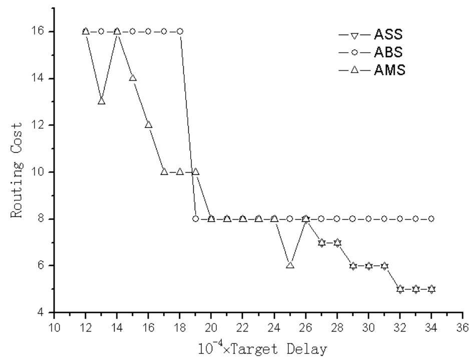


Figure5. Comparison for Routing Cost with different target delay

IV. PERFORMANCE EVALUATIONS

We implemented our adaptive spray mechanisms: ASS, ABS and AMS with Opportunistic Network Environment, ONE [23]. We evaluated the performance in terms of capacity of delay constraint, scalability and adaptability in different scenarios. Table 1 has shown the simulation parameters (some parameters were given in the following section since they are related to special scenario). All the performance results presented are an average of 10 different simulation trials. The initial locations of the network in each trial are random.

Table 1: simulation parameters

parameters	**Value**
Group.movementModel	RandomWaypoint
Group.speed	0.5,1.5
Group.waitTime	0
MovementModel.worldSize	400, 400
Group.nrofHosts	100
Router.nrofHosts	100

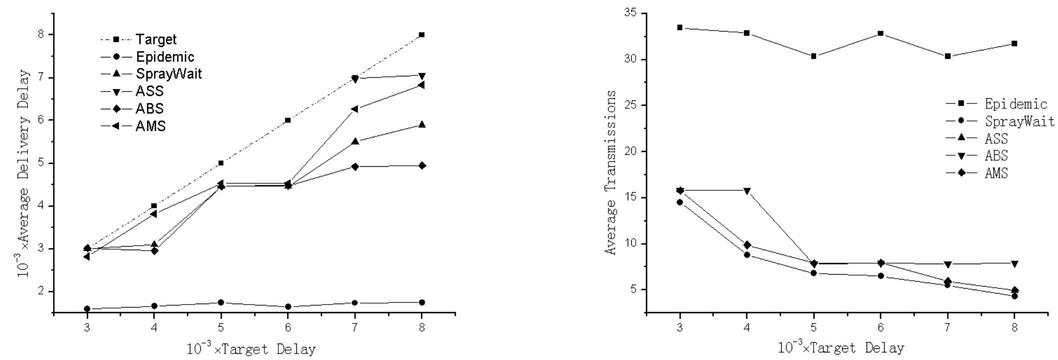
Events.size	500kB, 1MB
Group.transmitSpeed	250kbps
Events.interval	2000-3000
Events.hosts	0,99
Group.msgTtl	20k
Group.transmitRange	10
Group.targetDelay	11k
simulationTime	2* Group.targetDelay

a. Delay Performance

In this scenario, we evaluated the delay constraint performance of adaptive spray mechanisms. We tested the average delivery delay and average transmissions with different target delay, denote as D_t (3k-8k). Each node created messages from time 0 to D_t for every 2000-3000 time units.

The simulation results depicted by figure 6 have shown that Epidemic routing which is lack of control mechanisms for message copies performed significantly more transmissions than spray based routing, however it is quite fast. We can see that ASS can't satisfy the small target delay (<7000) due to the serial spraying which needs more time to accomplish spray phase. On the other hand, ASS outperforms all protocols in terms of average transmissions since there is no copy redundancy in whole spray process. Spray&Wait, ABS and AMS can satisfy all different target delay from 3000 to 8000. Spray&Wait and ABS can achieve good expected delay among all spray based routing mechanisms since it carries out binary spray. *Theorem 3.1.1* has proved that AMS is equivalent to ABS when there are enough seeds. It implies that AMS and ABS have the same capacity of delay constraint. Furthermore, ABS performed more transmissions than AMS and ASS, while outperformed all adaptive spray mechanisms in terms of average delivery delay. This is because ABS produced most redundant copies which caused extra transmissions and reduced the average delivery delay at the same time. Spray&Wait was not an adaptive spraying and calculated the minimum number of copies in the source node. So Spray

& Wait show the least routing cost when the network circumstance was static.



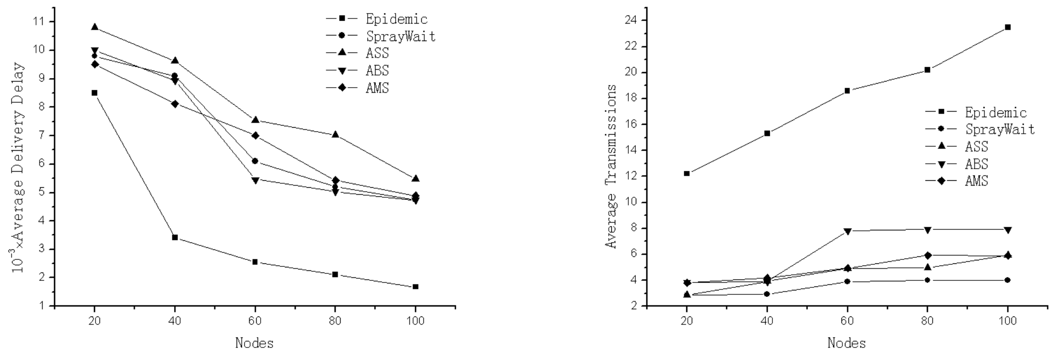
(a) (b)

Figure6. Performance comparisons with different delay constraint

b. Scalability

We evaluated the scalability with different network scale (20-100 nodes). As shown in figure 7, all protocols can achieve the delay constraint with increasing scale of network. Furthermore, we denote γ as the radio of the average transmissions and the number of nodes. It is important to note that γ will reduce with increasing network scale. For more accurate, γ reduced from 14.4% to 5.936% in ASS, from 19.14% to 7.938% in ABS and from 18.98% to 5.906% in AMS when the nodes increased from 20 to 100. This means our adaptive spray mechanisms can meet the more stringent delay constraints in large-scale networks. Therefore, adaptive spray mechanisms have excellent scalability.

Further more, we can see from figure 7, the transmissions of ABS varied more significantly than ASS and AMS. *Theorem 3.1.1* had shown that the routing cost of ABS was an exponential form with the depth of spray, while the routing cost of ASS was a line form and AMS is moderate too. It implies that the average transmissions of ABS vary more significantly than ASS and AMS since the number of copies in adaptive spray mechanisms depends on the depth of spray. This also brings about the differences in terms of *Average copy redundancy*.

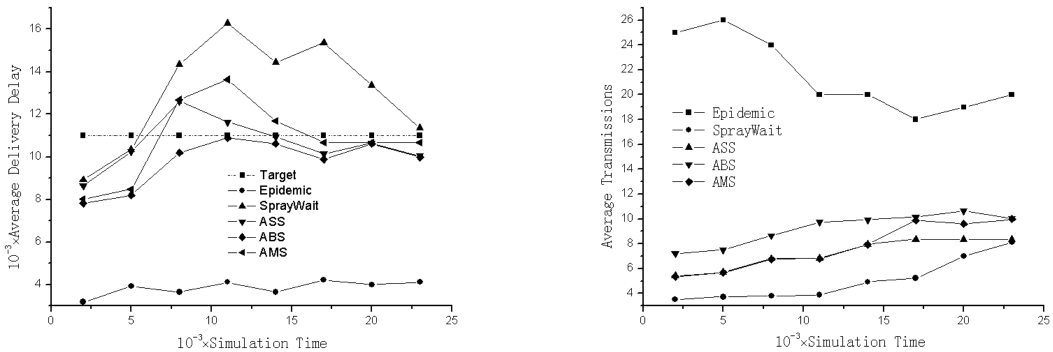


(a) (b)

Figure7. Performance comparison with different network scale

c. Adaptability

In opportunistic networks, network connectivity may change sometimes, for example, the change of work mode for special applications, low-power transmission mode due to lower energy, sleep scheduling mechanism, etc. To evaluate the performance with dynamic connectivity, we decreased the transmission range from 10m to 2m at $D_t/2$. Figure 8 depicted the performance of all routing algorithms in terms of average number of transmissions and average delivery delay in this scenario. As can be seen there, the average transmissions of spray protocols increased when the transmission range decreased. This is because *EMT* and corresponding delivery delay will increase when the transmission range decreased. This implies it is necessary to add extra copies to meet the target delay. On the contrary, the transmissions of Epidemic Routing decreased due to the specific value of *TTL*. Since Spray&Wait decides the number of copies in source node, it also can’t apperceive the change of transmission range. Therefore, Spray&Wait don’t have good ability to adapt the evolvement of networking condition. Especially, the delivery delay of Spray&Wait exceeded the target delay most of the time. Spray&Wait needs more time (>22k) to make new decisions for spraying. On the other hand, all adaptive spray mechanisms can meet the target delay again before 16k time units.



(a) (b)

Figure8. Performance comparisons with dynamic connectivity level

V. CONCLUSION

A class of adaptive spray mechanisms in opportunistic networks was proposed in this paper. Adaptive spray mechanisms use relay nodes to make spray decisions in order to apperceive the change of network conditions exquisitely, and are least-cost delay-bounded routing protocols under specific spray mechanisms. Theoretic analyses of adaptive spray mechanisms were also given in this paper at aspects of routing cost, copy redundancy and expected delay. Simulation results have shown that: (1) adaptive spray mechanisms performed significantly fewer transmissions than epidemic routing; (2) adaptive spray mechanisms shown prominent superiority in adaptability for dynamic networks; (3) adaptive spray mechanisms exhibited great scalability; (4) adaptive spray mechanisms were a class of efficient delay-bounded routing mechanisms for opportunistic networks and are suitable for different applications. Specifically, ASS is efficient in resource sensitive opportunistic networks with relaxed delay constraint. Contrarily, ABS is suitable for the case with strict performance constraint. AMS is a more general and flexible adaptive spray routing.

ACKNOWLEDGEMENT

The subject is sponsored by the National Natural Science Foundation of P.R China (No. 61100199, 61100213, 60973139, 60903181, 61003039), talents project of Nanjing University of Posts and Telecommunications(NY210077), the Open Research Fund from the Key Laboratory for Computer Network and Information Integration (Southeast University), Ministry of Education, China(K93-9-2010-13), the Open Research Fund from the State Key Lab. for Novel Software Technology(Nanjing University)(KFKT2011B20), China Postdoctoral Science Foundation funded project(20110491453) and Jiangsu Planned Projects for Postdoctoral Research Funds(1101126c).

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