END-TO-END DELAY DIFFERENTIATION BY PRIORITIZED MULTIPATH ROUTING IN WIRELESS SENSOR NETWORKS

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ABSTRACT

The wireless sensor network has received increasing attention recently. Due to the inexpensive cost and small size of sensor nodes, sensor networks are densely deployed in many applications. Performing multiple tasks, the traffic generated by the wireless sensor network is hybrid, including time-sensitive traffic and delay-tolerant traffic. Obviously, handling them in a uniform fashion is unsuitable. Our objective is to provide classified service according to the attribute of packets. In our paper, we utilize the multiple paths between the source and sink to provide a solution satisfying the delay requirements of different traffic types. In dense wireless sensor networks, this is feasible because numerous paths exist between a source node and the sink. We propose a model for multipath routing, followed by detailed explanation of our routing protocol PRIMAR (PRIoritize MultipAth Routing). Simulation results demonstrate the effectiveness of PRIMAR.

INTRODUCTION

In our paper, we consider the scenario of bursty traffic instead of light load in wireless sensor networks. When spatially scattered multiple incidents simultaneously arise in a sensing field, a large amount of data would be procreated by sensors. Although we can take advantage of data aggregation to reduce the redundancy in the raw data from the same area, this technique is not very efficient if data sources are independent. For example, sensors detect concurrent multifarious anomalies in distinct regions respectively. Since those events are independent, heavy traffic load is inevitable when many sensors report to the sink and no complimentary policy is implemented. Nevertheless, bandwidth and power are scarce resources in wireless sensor networks. For time critical applications, i.e. intrusion detection, disaster and emergency surveillance, the sensor network is not capable of carrying the load, which results in large end-to-end delay or packet loss rate. As the network is congested by injected packets, information which aids in locating the abnormities could be lost due to the event explosion. Even though the information reaches the sink finally, it is already obsolete for tracing the mobile targets and the damage may have spread over an extensive range. This wastes bandwidth and power, thus degrades the network efficiency. To ensure the effective functioning of wireless sensor networks, we attempt to protect crucial information while achieving best effort delivery of non-critical information.

Observing the hybrid traffic in a sensor network, carried content of packets predestines them for differentiated purposes. In general, some information is time sensitive, while other can bear a larger delay. Implicitly, packets are weighted disparate importance by their characteristics. It is not wise to treat miscellaneous traffic in a uniform fashion. For further efficient use of constrained bandwidth and energy at sensor nodes, we exploit this feature through content-aware routing. Generally, packets bearing critical information are more valuable than regular periodic packets. Those critical packets appear with much smaller probability than periodic packets, so they have higher entropy and provide more information. We differentiate those critical packets from noncritical packets, which include packets missing the performance requirement and packets carrying noncritical information. In other words, we want to provide preferential treatment to packets based on the content they carry. Numerous routes exist between each source and sink pair. In terms of performance, those routes behave remarkably different. Intuitively, the difference in packet content can be translated into the different choice of route.

The rest of the paper is organized as follows. Section II discusses previous work on related topics. Section III describes our proposed routing protocol PRIMAR. Section IV illustrates the simulation and discusses the simulation results. Section V concludes the paper.

RELATED WORK

Multipath routing has been studied in ad hoc networks for a long time. In TDMA networks, QoS routing protocol[1] examines common free slots of two neighbors and allocates bandwidth along the route from the source to the destination on demand for connection admission control. Nevertheless, on-demand routing induces unbearable delay at the connection establish stage. It is energy-consuming as well. When a link breaks, it restarts route discovery from the source to the destination again. Many routing protocols tailored for wireless sensor networks have been proposed. Both single path and multipath routing are explored to provide energy efficient, reliable and low latency service. By constraining the maximum transmission distance[2], the authors explore the relation between transmission range and energy efficiency. To maximize the information gain while minimizing latency and bandwidth consumption, Information Driven Sensor Querying (IDSQ) and Constrained Anisotropic Diffusion Routing (CADR) mechanisms were proposed by Chu et al.[3]. Selecting an optimal subset of sensors according to defined information utility measures, the querying node sends queries along routes to those sensors through a gradient-based routing algorithm. In [5], SWR is a scheme designed to repair the pre-established route to provide guaranteed delivery of packets with low energy consumption. Previous protocols treat all packets in the same fashion. While the main goal of our scheme is to differentiate packets through multipath routing.

Packet redundancy is utilized to satisfy different desired reliability for prioritized packets [6]. Nodes adaptively forward a packet with probability. But a centralized node is deployed to compute the adaptive probabilities and control the forwarding behavior of other nodes. This produces considerable overhead in the network and is susceptible to single point of failure. Kannan et al.[8] introduce Quality of Routing(QoR) to establish the optimal routing architecture. Sensors are modeled as ‘smart’ agents and motivated by self-interest, which means they trade individual communication cost for network wide benefits. A novel scheme, SPEED[9] supports soft real-time communication by maintaining a desired delivery speed across the network based on stateless greedy routing algorithms. However, greedy routing may overlook some feasible paths and drop packets which can be delivered to the destination.

Multipath routing mechanisms [10][7][11][12] address the reliability problem in wireless sensor networks. In [7], multiple copies of a packet are sent on several forwarding paths to achieve the desired reliability. The number of paths in use is determined based on local knowledge of the channel error rate. This method incurs remarkable overhead especially when channels are bad. It is not very efficient if there are inherent high redundancy in packets. In [10], multiple backup routes are set up at the routing establishment stage for purpose of resilience. Braided multiple routes can balance load and improve reliability. Those alternative routes are just good in sense of “local” instead of the idealized end-to-end counterpart. Constructing a route mesh [11] between a source and destination, each node selectively forwards a packet among multiple routes based on local conditions. By diversity coding, a data packet is split up into smaller subpackets of equal size with added redundancy [12]. The number of subpackets corresponds to the number of outgoing paths. Though some of the subpackets may be lost, only part of them are required to reconstruct the original packet at the destination [4]. Our protocol is distant from all these multipath mechanisms. Because the main goal of them is reliability but information-aware routing. They treat all packets in the same manner, regardless of disparate contributions of packets to the application.

PRIMAR PROTOCOL

Aiming at providing differentiated service in the sensor network, information-aware classification of packets is employed. Here we assume that the source node has the knowledge of the importance degree of packets it generates. Content-awareness can be achieved in the framework described in [13]. A priority field, stamped by the origin node, is included in every packet to classify packets. The more important the packet is, the higher priority is assigned to it. Low priority packets take a longer route to make way for high priority packets. In this paper, we assume that the priority level goes down from 1 to M, where M is the maximum integer value of the priority level. Packets of the highest priority are forwarded on the “optimal” path among the m-paths to the sink. Here we refer to the “optimal” path in sense of the path with the shortest end-to-end delay. Certainly, this definition also applies to other metrics, like error rate et al. We focus on the end-to-end delay in this protocol.

A. m-paths Initialization

First of all, each node needs to construct a routing table describing the delay of each outgoing path. Since there are M priorities, each node seeks for M routes. But the number of neighboring nodes, say k, may be less than M. In that case, the number of routes is decided by $m = \min(M, k)$. All lower priority packets are forwarded on the *mth* routes. A route entry has the form of (Priority, NextHopNode, Delay). Delay is referred as the end-to-end delay from

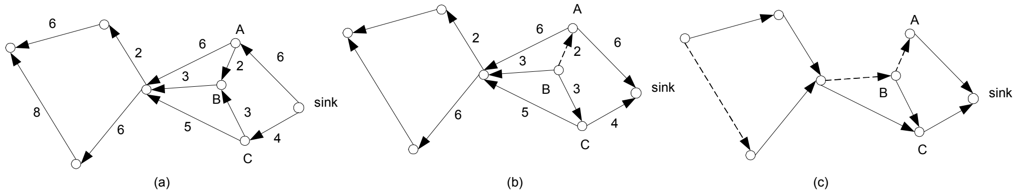

Figure 1. (a) Topology is labeled with delay cost. (b) Route discovery begins from neighboring nodes of the sink and back propagates across the whole network. (c) The finally formed multiple paths.

current node to the sink. When receiving a packet, the node checks the priority of the packet and forwards it to the corresponding next hop node when the channel is available. Since the delay may vary with environment, so an average delay is used. The path establishment process is similar to the Bellmanford algorithm, except that M shortest paths are set up at the same time.

Launching at the sink, the delay back propagates in the sensor network until all nodes finish this process. Fig. 1 illustrates the process of m-route discovery. For simplicity, we use *m*=2. Fig. 1. (a) shows the delay cost of all links. The finalized paths are indicated in Fig. 1. (c). Since node A is a neighbor of the sink, there is only one route from node A to the sink. Whatever the priority is, the packet is forwarded to the sink on the same route. Node C is similar to node A.

At the end of the route discovery phase, every node establishes a routing table as Table I.

TABLE I. an example of routing table

Priority	NextHopNode	Delay
1	A	2
2	F	3
⋮	⋮	⋮
m	C	8

B. Priority Level Slicing Model

At the end of the route establishment stage, every node connects to the sink through M routes. If we deal with the whole M sets of routes concurrently, it would be very sophisticated and bewildering. So we use "priority level slicing" to gain a plain view of the connectivity graph. In "priority level slicing", the entire route graph is sliced into M layers corresponding to M priority levels. In the lth layer, only routes with l priority level present. Fig. 2 shows the layering of a topology with two priority-level routes. In this way, we decorrelate M level routes and handle those layers separately. Every layer has a much simpler topology than the unsliced one. Combining all those M layers, we get the original path "map" of the whole network. Apparently, the topology change in one layer is isolated from other layers. The multipath routing is simplified to multiple parallel single path routing instead. Consequently, slicing facilitates the maintenance of the intricate topology due to the large amount of paths. The sensor network is modeled as a directed graph $G = (V, E)$, where V is the set of vertices (nodes) and E is the set of all edges (links). Let E_p be the set of paths with priority p. Actually, the topology of every layer is a directed-out tree, which is rooted at the sink and reaches all nodes.

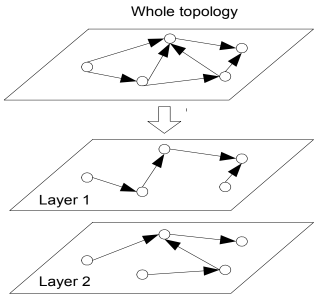

Figure 2. Shows sliced layers with corresponding priority routes extracted in each layer.

C. Energy-aware Route Borrow

1) Route Borrow: Our scheme is designed to meet the end-to-end delay demand of differentiated packets. So in the previous section, prioritized routes are established to serve this purpose. After that, an intuitive manner to perform routing is to route packets at each layer according to their priorities. This simple method can achieve good performance under uniform traffic pattern, because no layer would experience starvation. However, because of the fluctuating traffic load and varying link condition in wireless sensor networks, the scheme may not behave well. On some occasions, a link is temporarily experiencing a large delay, a packet cannot be delivered on time if still go through that path. For example, event explosion causes heavy traffic load throughout the sensor network, in an extreme, the optimal route is saturated or the packet loss rate is surprisingly high on that route. Besides, if a node is in the process of route recovery and the failed optimal route is temporarily not available. In order to deal with those short-term path degradation or unavailable situations, route borrow mechanism is employed. The idea of route

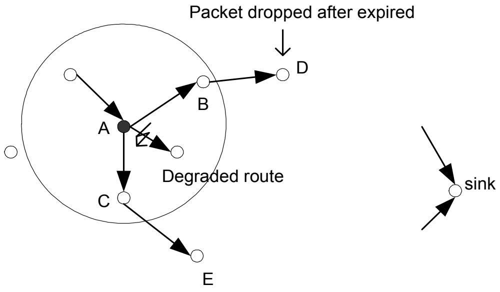

Figure 3. Node A is temporarily experiencing a large delay, so node B and C help forward the packet with probability. At node D, the packet expires and is discarded.

borrow is to utilize other available and capable paths to assist the degraded path with packet delivery.

- Upon receiving a packet with priority p, the node first checks if the packet expired or not. If the packet has already expired, the node discards it.
- If it is not, then the node compares the end-to-end delay requirement to the delay cost in the routing table. If the delay is smaller than the delay requirement and the corresponding route is stable, the packet is simply transferred at the corresponding pth layer. Routes work in a way similar to the virtual circuits. The stability of a path can be monitored through feedback information from the next hop node.
- Otherwise, currently the corresponding route is temporarily unavailable or experiencing degradation. Then the packet is broadcast by current node. Neighboring nodes hearing it help forward this packet with probabilities inverse to their delays as shown in (1). A node with a low delay helps transfer the packet with higher probability. But the predecessor of the broadcasting node would discard this message to prevent loops.

2) Energy Balancing: Energy is a crucial design issue in wireless sensor networks. Lower quality paths survive for a much longer time. On the other hand, nodes on high quality paths deplete energy faster because they are more desirable and prone to helping forward packets of other nodes. If energy is not taken into consideration, those nodes would wear out energy quickly. Substituting "optimal" paths with suboptimal ones increases the end-to-end delay. If an optimal path breaks down due to some critical nodes on that path wearing out of energy, emergency packets may never reach the sink. Because of relative larger delay of other paths, a packet would be dropped if an immediate node judges it as an expired one. As shown in the following section, paths repair affects too many nodes, thus consumes considerable amount of energy. Therefore preserving current good paths gains advantage over repairing paths. Route maintenance is executed only when it is unavoidable. So the power level must be considered as a factor in determining the forward probability shown in (1).

$$P_f(j) = \begin{cases} (1 - \frac{D(j)_p}{D_r})\frac{E_r}{E}, & \text{if } D(j)_p \leq D_r \\ discard, & \text{otherwise} \end{cases} \qquad (1)$$

where $P_f(j)$ is the probability to forward the packet. Denote E_r the residual energy level of the help forward candidate node. Let E be the total energy of a node at the very beginning. D_r indicates the delay required to deliver this packet from current node to the sink, which can be computed through

$$D_r = E2ED_{requirement} + Timestamp - Time_{Current}$$

The expected number of the copies can be obtained by

$$E[\text{number of copies}] = \sum_{j=1}^{k-2} P_f(j) + 1$$

So the help forward probability is proportional to the relative remained energy at that node. If the energy level is too low, it is unlikely that the node would forward the packet for other nodes. This mechanism adaptively spreads packets on possible routes to achieve better end-to-end delay performance while trying to prolong the lifetime of each route simultaneously. Therefore load adaptively deviates from incapable and low power nodes. After performing route borrow at a few hops, the load spreads to a wide area. Any intermediate node will reject the expired packet, which is shown in Fig. 3. Consequently, the sink would not receive excessive duplicates of the packet as many routes cannot deliver the packet timely. As several replicas are forwarded along different routes in the network, reliability is enhanced by spatially distributing packets. A node may receive multiple copies of a same packet. But it only forwards the very first received packet and discards the following ones. The sequence number of the packet is kept for time D_r, because after that period the packet will timeout. Even the node receives the packet again after time D_r, it would be discarded immediately. So network wide flooding would not happen. Another benefit of the route borrow is congestion control. Load is sipped by a traffic deserted area to alleviate the burden of congested nodes. These are all achieved at the single corresponding layer. Every layer operates in the identical way separately.

D. Route Maintenance

Maintaining multiple routes in the network is a tough issue. Even though some papers touch this issue[1], solutions for wireless ad hoc networks are not suitable for sensor networks due to constrained energy and computational capacity. In [5], a route repair method dealing with the single path routing has been proposed, but it cannot solve more complex counterpart problem in multipath routing. After operating for some time, some routes do not satisfy the delay requirement anymore or a route fails due to topology change. Thereby, route maintenance is invoked.

1) Delay update: If delay changes, delay is updated at the end of data transmission. In each acknowledgement, the successor node s feedbacks its current Delay $D(s,t)$ as well. Current node i uses it to update its own delay to the sink. Since delay changes with time, we assume it is a function of time, $D(i,t)$. Exponential average end-to-end delay is used in the routing table to smooth unpredictable delay variations.

$$D(i,t)_p = \alpha D(i,t-1)_p + (1-\alpha)(D(s,t)_p + l(i,s,t)) \quad (2)$$

where the link delay $l(i,s,t) = \frac{1}{2}RTT(i,s,t)$. Denote $RTT(i,s,t)$ the round trip time from i to s at time t. p indicates the corresponding priority. The end-to-end delay deviation $D_\delta(i,t)p$ is

$$D_\delta(i,t)_p = \beta D_e(i,t-1)_p + (1-\beta)|D(i,t)_p - D(i,t-1)_p| \quad (3)$$

Here α and β are forgetting parameters.

2) Route repair without node failure: To repair a path, we need to find out an alternative route of the same priority. With slicing model, routing repair occurs at the corresponding layer if a certain priority route degrades. At that layer, the problem reduces to the single path rerouting, which is easier to deal with. A path is recovering, remaining paths at other layers unaffected.

The node detecting the degraded route broadcasts a packet, including routing information of the degraded route. The node also sets a timer for response. Upon receiving the request, other nodes except upstream nodes and the downstream node to be substituted, reply to the requesting node with the *pth* route entry and nominate themselves as candidates of the alternative route, if available. If no response is received after timeout, this indicates that there is no neighboring node on that layer. Then all upstream nodes of it cannot connect to the sink. The requesting node moves all the successive routing entries of p a priority ahead, i.e. the *p+1*th entry becomes the pth entry. If the requesting node receives responses, it chooses the one with the lowest delay as the new path and updates the *pth* routing entry. After that, the node informs the upstream nodes with the delay change, in the acknowledgement of a data packet to its immediate upstream nodes. Nodes on the path repeat this process until all related nodes are notified.

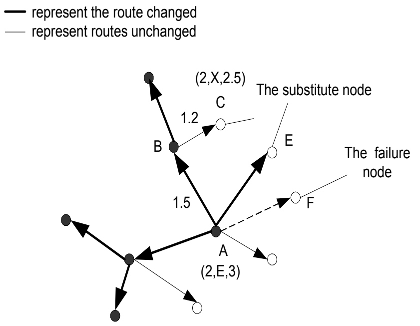

Figure 4. Spread of route changes in the network without control, which influences routing of nodes exponentially.

3) Node failure: The routing maintenance process is similar to the previous one except that all m layers perform the same operation synchronously, which starts at all predecessor nodes of the failed node. The total number of predecessor nodes is equal to the sum of the predecessor node at all m layers. In other words, the input degree of the failed node.

Unfortunately, change of the routing table at one node induces sequential changes at other nodes. For example, in Fig. 4, node A changes the 2nd entry cost from 2 to 3. It may no longer be the best next hop node of B. Then B broadcasts a packet to inquire who is the best next hop node. After message exchange, it changes the next hop node of the 2nd entry to C. Variation of costs at a node may alter the cost fields of routing entries of many neighboring nodes of it. In return, change at those neighboring nodes waves ahead and impels their own neighbors to change routing entries. As the change spreads in the network, more nodes are involved and flooding arises, which is shown in Fig. 4.

To alleviate the traffic storm owing to this phenomenon, guard delay D_g is used as a complimentary measure. The guard delay is defined as the delay variance in (3), which indicates the threshold of delay fluctuation. A delay change larger than D_g implies a critical variation. Only when the change is beyond D_g or the new cost is higher than that of the next lower priority level, routing table changes. This accelerates the convergence of the network and greatly lessens the overhead. Though the elected route is not permanently the best one available, generally routes are classified according to their qualities. Essentially, quality of routes is traded for decreased traffic and rapidness of convergence.

Maintain current route, if $| \; D(i,t)_p - D(i,t-1)_p \; | \leq D_\delta(i,t)$

Update route, otherwise.

Without the guard delay scheme, the incurred overhead to update routes exponentially increases with the number of hops that the change propagates. However, the guard delay inhibits this disaster by restraining the radius that the route refresh procedure disseminates.

SIMULATION

We simulate our scheme on GloMoSim, which is a scalable discrete-event simulator from UCLA. We compare PRIMAR with routing protocol DSDV[14]. 100 nodes are uniformly deployed in a field of $200m \times 200m$. IEEE 802.11 is used as the MAC layer protocol. The node transmits data packets, which have size of 32 bytes with bandwidth of 200kb/s. The transmission range is 40 meters. We randomly choose 10 flows with the packet generation rate of 1Packet/S. The generated packet randomly chooses priority from 1 to 3. To test performance under different congestion conditions, we randomly choose another node to generate packets at the speed of 1Packets/S. Then the generation rate increases gradually to 100Packets/S. The measuring metrics are E2E delay, packet loss rate, delivery ratio, control overhead and the number of outage nodes.

A. E2E Delay

While DSDV has an average delay fluctuating above that of priority 2 of PRIMAR. For PRIMAR, packets with priority 1 has the lowest E2E delay, followed by priority 2, with priority 3 the highest. The delay reaches its peak at 30Packets/s, indicating that the network is congested with the offered traffic load. Other figures demonstrate the situation too. Fig. 5 shows that the end-to-end delay remains stable against the traffic intensity in PRIMAR.

B. Packet Loss Rate

Packet loss rate is the ratio of the number of packets dropped before arriving at the sink node to the total number of packets generated at all source nodes. Therefore it includes packets violating the delay requirement. PRIMAR behaves better than DSDV in terms of packet loss rate for both under-saturated and over-saturated load. The packet loss rate of PRIMAR is comparable to DSDV around saturating points. Again, the packet loss rate skyrockets to about 15% when the traffic load increases to 30Packets/s. The network is saturated at this traffic intensity.

C. Delivery Ratio

Delivery ratio is defined as the number of received packets of a particular priority satisfying the specified delay requirement to the total number of packets of that priority generated by all source nodes. PRIMAR changes abruptly at packet rate of 30Packets/S, which is due to the sudden increase of packet loss rate. Since DSDV does not perform different routing for prioritized packets, their delivery ratio are almost the same. We just show the delivery ratio of one of the three priority for DSDV. It is seen that packets with priority 1 of PRIMAR is superior to DSDV, but packets with lower priorities have lower delivery ratio than DSDV. Both Fig.5 and Fig.7 manifest the distinct behavior of different priorities in PRIMAR.

D. Control Overhead

PRIMAR shows greater advantage over DSDV in terms of control overhead. For PRIMAR, the control overhead is mainly introduced at the initialization stage and congestion situation. So it increases gradually with the traffic intensity. But for DSDV, besides the control overhead for initialization and congestion, the periodical broadcast update from the sink contributes to higher control overhead than PRIMAR.

E. Exhausted Nodes Percentage

To compare the network lifetime, the percentage of nodes wearing out of energy against traffic intensity is plotted in Fig. 9. The number of failed nodes directly affect the functioning of the wireless sensor network. PRIMAR is comparable to DSDV in network lifetime, while achieves service differentiation. The simulation result demonstrates that PRIMAR achieves service differentiation with enhanced performance compared to DSDV.

CONCLUSION AND FUTURE WORK

Many novel protocols have been designed for wireless sensor networks to meet the challenging of differentiated routing. Our scheme shows good performance in simulation. The major contributions of our work are three-fold. First, we propose a pellucid method to look into the multipath routing problem, which is inherently very complicated. Second, our scheme provides differentiated service to meet the demand of various applications and services. Third, PRIMAR also mitigates the effect on time-sensitive packets of congestion.

We can further improve our protocol if we combine MAC layer into it at the same time. The cross layer design is a feasible way to decrease packet loss rate and packet miss ratio, especially at high packet rate situation.

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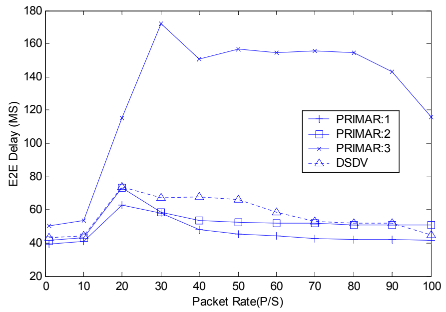

Figure 5. E2E Delay VS Packet Rate

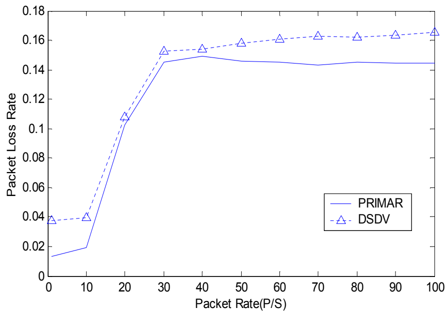

Figure 6. Packet Loss Rate VS Packet Rate

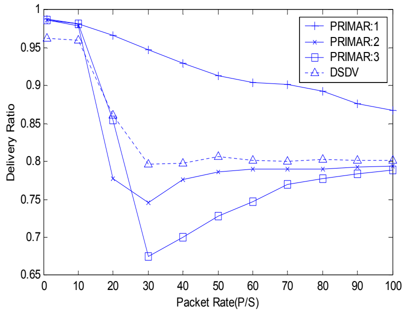

Figure 7. Delivery Ratio VS Packet Rate

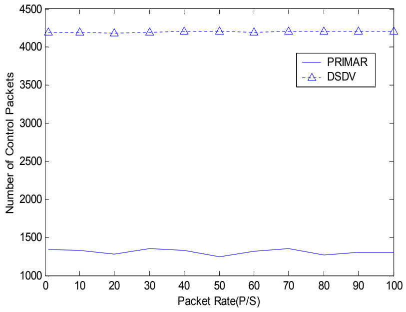

Figure 8. Control Overhead VS Packet Rate

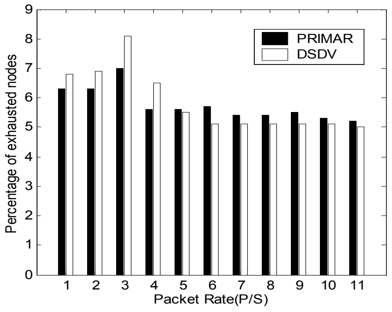

Figure 9. Exhausted Nodes VS Packet Rate

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