Optimal Remote Homing for Providing Service Differentiation in Information-Aware Multi-Layered Wireless Sensor Networks

Jianping Wang
Department of Computer Sciences
Georgia Southern University
Statesboro, GA 30460
Email: jpwang@georgiasouthern.edu

Vinod M. Vokkarane
Department of Computer and Information Science
University of Massachusetts Dartmouth
North Dartmouth, MA 02747
Email: vvokkarane@umassd.edu

***Abstract*— Sensor networks are fundamentally deployed to handle extreme behaviors across sensing sites. Service differentiation in information-aware wireless sensor network refers to the ability to provide reliable and low-latency transmissions of critical data. In this paper, we present remote-homing based solutions to support service differentiation in wireless sensor network. For each sensor (source), we designate remote homes that bypass certain layers in a multi-layered sensor network in order to reduce transmission delay, and also identify node-disjoint remote homes in order to provide high reliability. We develop algorithms that identify optimal remote homes, which minimize the total energy consumed for data transmission given a delay and a loss constraint. We evaluate the effectiveness of our dynamic programming-based optimal algorithms using simulation results.**

I. INTRODUCTION

Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power, small-size, and multi-functional sensor nodes. These tiny sensor nodes that are deployed in an ad hoc fashion and that cooperate on sensing a physical phenomenon, have led to the emergence and deployment of wireless sensor networks. Sensor networks hold the promise of revolutionizing sensing in a wide range of application domains because of their reliability, accuracy, flexibility, cost-effectiveness, and ease of deployment [1].

In a large-scale sensor network, multi-layered architecture is usually adopted to provide scalability [2]. Multi-layered architecture partitions sensor nodes into different layers according to their hop counts to the sink (base station), where one hop-count path means that the sink is within transmission range of the source. Data is forwarded from source to sink through those nodes with lower hop counts to the sink. In a multi-layered architecture, all the sensor nodes that send data to the same higher-layer node form a cluster with the cluster-head being the node closest to the sink. The multi-layered architecture can provide scalability and energy efficiency, since information is disseminated through multi-hops instead of single hop, but introduces a longer delay. The information dissemination (routing) paths form a tree rooted at the sink in the multi-layered architecture.

For information dissemination in wireless sensor networks, it is important to send critical information back to the sink with high reliability and low delay. Consider an application that monitors temperature in a forest so as to detect forest fires. The sensor has to differentiate between a temperature reading of 70^0F on a normal day from another reading of 1000^0F due to forest fire. From the point of view of the network, the packet reporting 1000^0F is much more important as it could indicate a forest fire (the purpose of deploying the sensor network in the first place). Hence, this data should reach the base station with high reliability and low latency.

To the best of our knowledge, there has not been too much research work done for providing service differentiation based on the importance of sensed information for wireless sensor networks. A few researchers have addressed the problem of loss differentiation using multi-path routing techniques [3], [4], [5], [6]. Also, some researchers have addressed problems of providing end-to-end reliable data transfer from the source to the sink using minimum retransmissions [7], [8], [9]. Recently, [10] and [11] address the issue of delay differentiation in ad hoc networks. A framework is developed to provide delay differentiation in ad hoc sensor networks by associating a power budget with every message. Given a power budget and a source-destination pair, the authors formulate the problem of finding the minimum delay (number of hops) route that satisfies the power budget constraints. The fundamental drawbacks of this framework are that it is hard to predict the power budget for each message based on the information-specific delay requirement, and the framework is only applicable to a certain symmetric network topology.

In this paper, we aim to provide an integrated loss and delay differentiation framework using the concept of remote-homing in multi-layered wireless sensor networks. In particular, each source sensor has a local-home that resides in the adjoining layer and a remote-home that resides more than one layer (hop) away in the multi-layered architecture. Each source node sends the normal traffic through its local-home to the sink with longer delay and low energy consumption. The source node sends critical traffic through its remote-home (bypassing certain layers in the information dissemination tree) with shorter delay and higher energy consumption.

We focus on identifying a remote-home for each node in order to satisfy a given delay constraint of critical data. We

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note that the chosen remote-home should minimize the total energy consumption along the path from the source to the sink (through the selected remote home) so as to prolong the lifetime of the sensor network. We also present a solution to identify dual remote-homes in order to support highly reliable and low-latency transmission for critical data.

The rest of the paper is organized as follows: Section II provides the description of the problem. An optimal solution is presented to identify a single remote home to provide delay differentiation for critical data in Section III. An optimal solution is given to identify two remote-homes for both delay differentiation and loss differentiation in Section IV. The implementation discussion is given in Section V. In Section VI, the proposed algorithms are evaluated using simulation results. Conclusions are given in Section VII.

II. PROBLEM DESCRIPTION

In this section, we provide a formal description of the problem of service differentiation in information-aware wireless sensor networks. Suppose there are H hops from a source to the sink in the information dissemination tree. Let the hops be denoted as $1, 2, \ldots, H$. Let Node 1 be the source sensor and Node $H+1$ be the sink. Let nodes on the path from Node 1 to Node $H+1$ be Nodes $2, 3, \ldots, H$ where the increase in node index indicates proximity to the sink. Let E_{ij} be the energy required to send a packet from Node i to Node j. We assume that the transmission energy is proportional to the square of the distance between the sender and the receiver [12], [13]. For a packet with a given priority, suppose that the maximum delay constraint in terms of the number of transmission hops is h. We then need to determine which remote home will be used to transmit the packet, so that the delay constraint is met and the total energy consumption is minimized. We refer to such a problem as *Single Remote Homing* (SRH).

The examples in Fig. 1 depict different energy consumptions required to transmit a data packet from Node 1 to Node 6. For a normal packet, as shown in Fig. 1(a), there are five hops between the source and the sink, and the total energy consumed along the path is 14 units. If the maximum hop constraint for a critical packet is two, we have several choices of remote-homes that bypass certain intermediate layers. One solution is given in Fig. 1(b) where Node 1 sends the packet to Node 4 (remote-home), and Node 4 relays this packet to Node 6. Under the assumptions that the energy consumed is proportional to the square of the distance, and the nodes are located approximately in a linear structure, the total energy assumption is 34 units. Another solution is given in Fig. 1(c) where Node 1 sends the packet to Node 3 (remote-home), and Node 3 relays the packet to Node 6, with 32 units of total energy consumed. If the design objective is to minimize the total energy consumption while satisfying the delay requirement, it is beneficial to select the latter solution given in Fig. 1(c).

In order to simultaneously provide delay and loss differentiation, we need to find a pair of node-disjoint paths such that they both satisfy the delay constraint and at the same time provide fault-tolerant data transmission. The idea is illustrated in Fig. 1(d) where Node 3 and Node 4 will be the dual remote-homes that forward data to the sink. We refer this problem of finding two node-disjoint paths with a delay constraint as *Dual Remote Homing* (DRH).

```
//Find $f(i,n)$ for $i = 1, 2, \ldots H+1, n = 1, 2 \ldots h$
for ($n = 1; n <= h; n++$)
    $f(H+1, n) = 0$
for ($i = H; i >= 1; i--$)
    $f(i, 1) = E_{i,H+1}$
for ($i = H; i >= 1; i--$)
   for ($n = 2; n <= h; n++$){
        min = INF;
        for ($j = H+1; j >= i+1; j--$){
            $tmp = E_{ij} + f(j, n-1)$;
            if ($tmp <$ min)
                min = $tmp$;
        }
    $f(i,n) =$min;
}
```

Fig. 2. Optimal single remote homing algorithm.

III. SINGLE REMOTE HOMING: DELAY DIFFERENTIATION

Recall that the distance from the source sensor to the sink in the information dissemination tree is assumed to be H hops. Suppose that a packet with critical information needs to be transmitted to the sink within h hops ($h < H$) with the minimum total energy consumption. Let the source be r_1 and the sink be r_{h+1}. Our work is to identify nodes $r_2, r_3, \ldots, r_h$ such that $\sum_{k=1}^{h} E_{r_k, r_{k+1}}$ is minimum among any possible r_k for $k = 1, 2, \ldots h$. Node r_{k+1} is the remote-home of Node r_k for $k = 1, 2, \ldots, h$.

Let $f(i,n)$ be the minimum total energy consumed for sending a packet from Node i to the sink within n hops. We have, for any $i = 1, \ldots, H+1$, $n = 1, \ldots, h$, the following dynamic programming recursion:

$$\begin{cases} f(i,1) = E_{i,H+1} \\ f(i,n) = \min\{E_{ij} + f(j, n-1) | j = i+1, \ldots, H+1\}. \end{cases} \tag{1}$$

Equation (1) gives the solution to identify Node i's remote-home, Node j, if no more than n hops can be used to transmit the information from Node i to the sink. Based on (1), we develop a bottom-up dynamic programming algorithm to calculate $f(i,n)$ as shown in Fig. 2 with the initial conditions for $i = H+1$ being $f(H+1, n) = 0$ for $n = 1, \ldots, h$. The time complexity for this algorithm is in $O(H^2 h)$ because there are $O(Hh)$ states to be calculated in (1) and each state is calculated in $O(H)$ time.

With the information of $f(i,n)$, the remote home of the source node will be Node r_2, if $f(1,h) = E_{1,r_2} + f(r_2, h-1)$. Correspondingly, the remote-home of r_i will be Node r_{i+1} if $f(i, h-i) = E_{r_i, r_{i+1}} + f(r_{i+1}, h-i-1)$ for $i = 2, 3, \ldots h-1$.

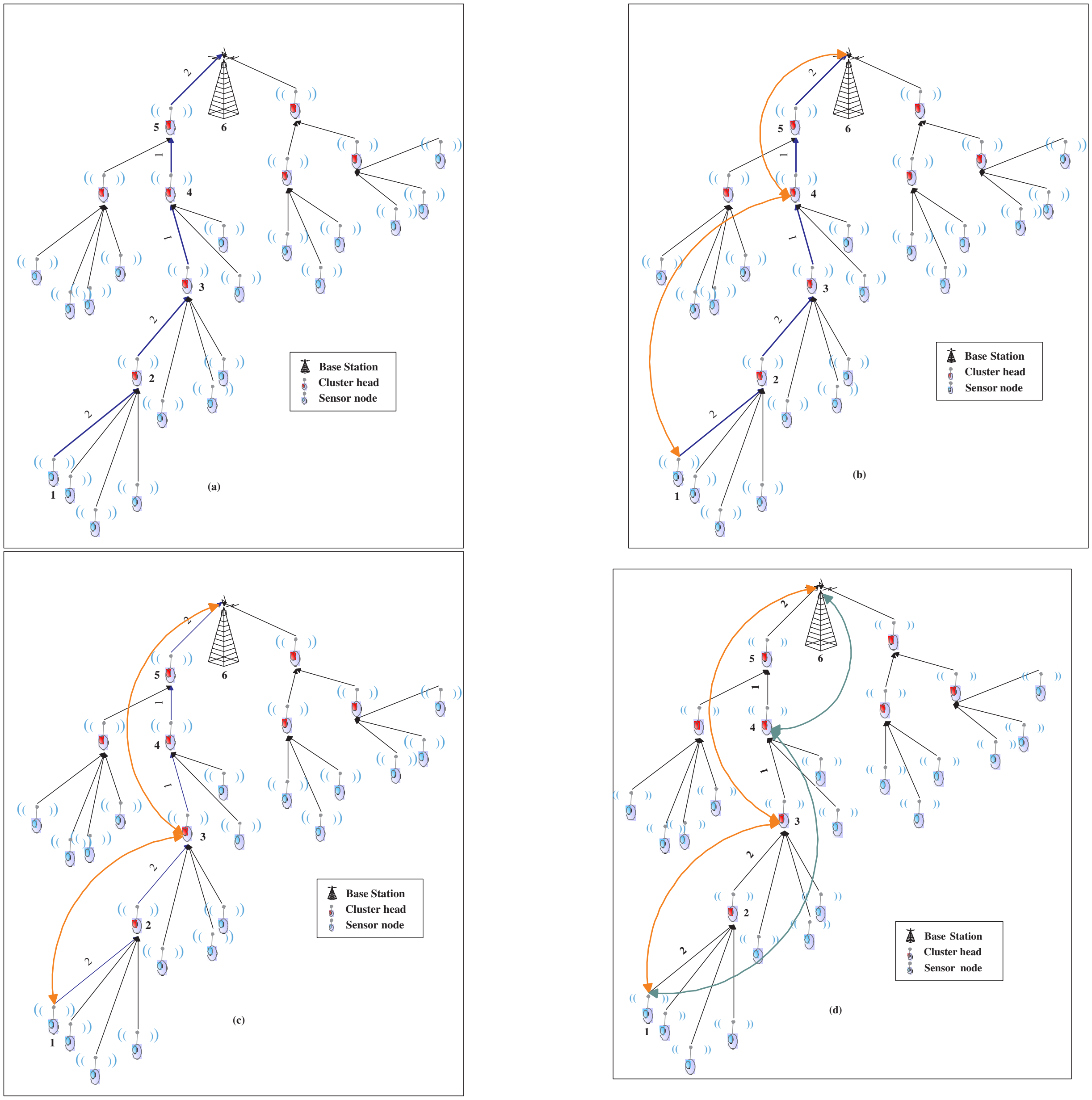

Fig. 1. (a) Information dissemination tree representation of a multi-layered wireless sensor network with a five-hop path from Node 1 (source) to Node 6 (sink). (b) A two-hop path that bypasses certain layers from Node 1 to Node 6. (c) Another two-hop path that also bypasses layers from Node 1 to Node 6. (d) Two node-disjoint paths between Node 1 to Node 6 with a maximum of two hops for enhanced loss-tolerance given a delay-constraint.

IV. DUAL REMOTE HOMING: INTEGRATED DELAY AND LOSS DIFFERENTIATION

Often it is important to support reliable transmission of packets with critical information such that they are tolerant against node failures along their path to the sink. To this end, we can set up two node-disjoint routes (dual routes), one being the primary and the other being the backup, and transmit critical data packets along both routes. When one node (any cluster-head in the networks) fails on one route, the critical information can still be delivered to the sink along another route. In general, we assume that based on the delay constraint the number of hops on the primary route cannot be more than h_1, and the number of hops on the backup route cannot be more than h_2, where $h_1 \leq h_2$.

There are several approaches to implement the dual routing in a wireless sensor network. One of the simplest approaches is to first set up the shortest primary route and then set up the node-disjoint backup route, each route found by the dynamic algorithm in Eq.(1), independently. However, as shown in the following example, this approach may be inefficient in terms of total energy consumption along the dual routes.

Suppose there are five hops from the source to the sink in the original information dissemination tree. Let the distance of each hop be one. Let $h_1 = h_2 = 3$. If we set up the primary route first, there are multiple optimal solutions. Suppose that we choose the primary Route as 1-3-4-6 with the total energy consumption of 9 units. Then the backup Route would be 1-2-5-6 with the total energy consumption of 11 units. Therefore, the total energy consumption for the two paths is 20. On the other hand, we have two other routes, where the primary Route is 1-2-4-6 and the backup Route is 1-3-5-6. This results in a total energy consumption of 18 units, showing that finding the two routes independently may lead to sub-optimal solutions.

We now develop an integrated dynamic programming based solution to find the two routes simultaneously, so that the total energy consumption is minimized.

Let (p, q) denote a pair of nodes, with p on the primary route and q on the backup route. We define $F(p, q, n, m)$ to be the minimum total energy consumed for sending a packet along the primary route from Node p to the sink within n hops and along the backup route from Node q to the sink within m hops. By the constraints of node disjointness, we known that the definition of $F(p, q, n, m)$ applies to $p = q = 1$, $p = q = H + 1$, and $p \neq q$ for $1 < p, q < H + 1$.

Let r be the source node's remote-home with a smaller index. By definition, $F(1, 1, h_1, h_2)$ is equal to $E_{1r} + F(r, 1, h_1 - 1, h_2)$ if r is on the primary path and is equal to $E_{1r} + F(1, r, h_1, h_2 - 1)$ if r is on the backup path. We recursively find the remote homes for r using the same approach. Therefore, our first task is to efficiently calculate $F(p, q, n, m)$ for $1 \leq p, q \leq H + 1$, $1 \leq n \leq h_1$, and $1 \leq m \leq h_2$.

We first consider the case when either $p = H + 1$ or $q = H + 1$. By definition, when $p = q = H + 1$, we have $F(H + 1, H + 1, n, m) = 0$ for any $n \geq 1, m \geq 1$. When $p = H + 1$ and $q < H + 1$, we have a dynamic program similar to (1),

$$F(H + 1, q, n, m) = f(q, m). \tag{2}$$

When $p < H + 1$ and $q = H + 1$, we have:

$$F(p, H + 1, n, m) \quad = f(p, n). \tag{3}$$

Now consider $f(p, q, n, m)$ for the case when $p, q < H + 1$.

Case 1 $p \leq q$: Note that p is equal to q only when $p = q = 1$. Consider the immediate next node, Node r, used by either the primary or the backup route. We know that $p < r \leq H + 1$ and $r \neq q$. Our dynamic program will enumerate all possible r and select the optimal remote node.

If $r < q$, then Node r can only be used by the primary route, given by:

$$g^1(p, q, n, m, r) = E_{pr} + F(r, q, n - 1, m). \tag{4}$$

If $q < r \leq H + 1$, then Node r can be on either route, and we need to select the better route where r can be placed. We denote this as:

$$\begin{aligned} g^2(p, q, n, m, r) = \min\{&E_{pr} + F(r, q, n - 1, m), \\ &E_{qr} + F(p, r, n, m - 1)\}. \end{aligned} \tag{5}$$

Combining (4) and (5), we define:

$$g(p, q, n, m, r) = \begin{cases} g^1(p, q, n, m, r) & \text{for } r < q \\ g^2(p, q, n, m, r) & \text{for } r > q. \end{cases} \tag{6}$$

Using $g(p, q, n, m, r)$, we have the following dynamic programming recursion:

$$\begin{aligned} &F(p, q, n, m) = \\ &\min_r\{g(p, q, n, m, r) | r = p + 1, \ldots, H + 1; r \neq q\}. \end{aligned} \tag{7}$$

Case 2 $p > q$: Consider the immediate next Node r to the source as a candidate for being the remote-home on either the primary or the backup route, $q < r \leq H$ and $r \neq p$.

If $r < p$, then Node r can only be used as a remote-home on the backup route, given by:

$$g^{1'}(p, q, n, m, r) = E_{qr} + F(p, r, n, m - 1). \tag{8}$$

If $p < r \leq H + 1$, then Node r can be on either one of the routes. We need to select the better route where r can be placed. we denote this as:

$$\begin{aligned} g^{2'}(p, q, n, m, r) = \min\{&E_{pr} + F(r, q, n - 1, m), \\ &E_{qr} + F(p, r, n, m - 1)\}. \end{aligned} \tag{9}$$

Combining (8) and (9), we define:

$$g'(p, q, n, m, r) = \begin{cases} g^{1'}(p, q, n, m, r) & \text{for } r < p \\ g^{2'}(p, q, n, m, r) & \text{for } r > p. \end{cases} \tag{10}$$

Using $g'(p, q, n, m, r)$, we have the following dynamic programming recursion:

$$\begin{aligned} &F(p, q, n, m) = \\ &\min_r\{g'(p, q, n, m, r) | r = q + 1, \ldots, H + 1, r \neq p\}. \end{aligned} \tag{11}$$

We also have boundary conditions of $F(p, q, n, m) = +\infty$ for either $n \leq 0$ or $m \leq 0$. The optimal solution can be found after calculating $F(1, 1, h_1, h_2)$. The time complexity of the optimal DRH algorithm is in $O(H^3h^2)$ because the number of $F(p, q, n, m)$ evaluations is in $O(H^2h^2)$ and each can be obtained from either (7) or (11) in $O(H)$ time. The algorithm description can be found in Fig. 3.

V. IMPLEMENTATION DISCUSSION

So far we have formally described the problem of the integrated loss and delay service differentiation for wireless sensor networks and develop optimal solutions based on dynamic-programming. The dynamic programming algorithms run in polynomial time. There is still one concern, however, with respect to implemetation. We observe that the proposed algorithms require the knowledge of the entire network topology in order to be optimal, which may not be the case in a sensor network. We now show that this concern can be handled by a revision of our dynamic program algorithms.

If a sensor only has limited information for its neighborhood, then the dynamic programming recursion (1) for single remote-homing can be revised to

$$f(i, n) = \min\{E_{ij} + f(j, n - 1) \text{ for } j = i + 1, \ldots, i + H(i)\}, \tag{12}$$

where $H(i)$ is the farthest node to which Node i knows that it can send information. Similarly, the dynamic programming for dual remote-homing can be changed when only local topology

```
for ($q = 1; q \leq H + 1; q++$)
    for ($n = 1; n \leq h1; n++$)
        for ($m = 1; m \leq h2; m++$)
            $F(H + 1, q, n, m) = f(q, m)$;

for ($p = 1; p \leq H + 1; p++$)
    for ($n = 1; n \leq h1; n++$)
        for ($m = 1; m \leq h2; m++$)
            $F(p, H + 1, n, m) = f(p, n)$;

for ($p = H; p \geq 1; p--$)
    for ($q = H; q \geq 1; q--$)
        for ($n = 1; n \leq h1; n++$)
            for ($m = 1; m \leq h2; m++$) {
                min = INF;
                for ($r = 1; r \leq H + 1; r++$) {
                    if (($p \leq q$)&($r < q$)){
                        tmp=$E_{pr} + F(r, q, n - 1, m)$;
                        if (min $>$ tmp) min = tmp;
                    }
                    if (($p \leq q$)&($r > q$)){
                        tmp=$E_{pr} + F(r, q, n - 1, m)$;
                        if (min $>$ tmp) min = tmp;
                        tmp=$E_{qr} + F(p, r, n, m - 1)$;
                        if (min $>$ tmp) min = tmp;
                    }
                    if (($p > q$)&($r < p$)){
                        tmp=$E_{qr} + F(p, r, n, m - 1)$;
                        if (min $>$ tmp) min = tmp;
                    }
                    if (($p > q$)&($r > p$)){
                        tmp=$E_{pr} + F(r, q, n - 1, m)$;
                        if (min $>$ tmp) min = tmp;
                        tmp=$E_{pr} + F(p, r, n, m - 1)$;
                        if (min $>$ tmp) min = tmp;
                    }
                }
                $F(p, q, n, m) =$ min;
            }
```

Fig. 3. Optimal dual remote-homing algorithm.

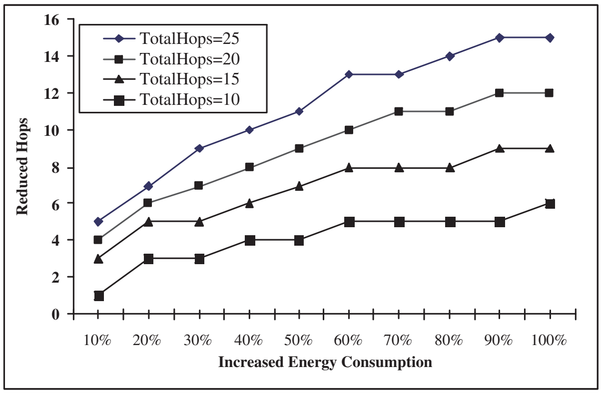

Fig. 4. Maximum reduced hops given the energy increase budget.

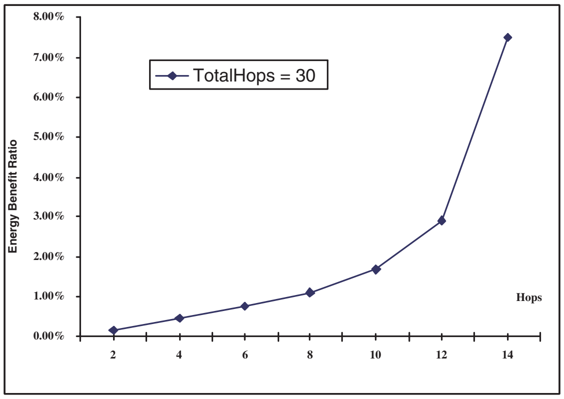

Fig. 5. Energy benefit ratio vs. number of hops reduced.

information is available at each node. We will compare the solution obtained from the local topology information with the solution obtained from the global topology information in Section VI.

VI. SIMULATION

In this section, we present simulation results for the proposed service differentiation algorithms. Our simulation is designed to address the following concerns.

1) Given the delay constraint (in terms of hops) for critical data transmissions and the additional power budget, we calculate the maximum number of hops that can be bypassed in the information dissemination tree in order to satisfy the requirements.
2) Given the delay constraint, we can find two node-disjoint paths either by using the optimal DRH algorithm or by using the optimal SRH algorithm twice. Since the time complexity of the optimal DRH algorithm is higher than that of the optimal SRH algorithm, in certain scenarios it is favorable to call the optical SRH twice. We compare the relative performance difference of implementing the simpler SRH algorithm as compared to the more complex, but optimal DRH algorithm.
3) Given a large-scale sensor network, we compare the relative energy benefit obtained by using the optimal algorithms that require the knowledge of the global topology information versus the performance with only local topology information.

In the simulation, a sensor network is generated as follows. Given the original total number of hops, H, we have nodes $1, 2, \ldots, H + 1$. Let Node i's position is specified by $[x_i, y_i]$ where Node 1's position is $[1, 1]$. In the simulation, we randomly generate Node $(i+1)$'s position to be $[x_i+\alpha, y_i+\beta]$, where α and β are uniformly distributed between $(0.0, 1.0)$. We assume that the energy required to transmit one data packet from Node i to Node j is calculated by $(x_j - x_i)^2 + (y_j - y_i)^2$.

Using the optimal SRH algorithm, we get the minimum energy consumption necessary so as to satisfy the given delay constraint, $h \leq H$. In Fig. 4 we can examine the maximum number of hops that can be reduced (from the original route) given a specific additional power budget. In Fig. 4, we observe that given 100% additional power budget, the number of hops along the path from the source to the sink can be reduced by more than 50%. We also observe that given 60% power increase, the ratio of number of reduced hops and additional energy consumed is maximum (about 50%). We note that the performance results is dependent on the network topology, the traffic pattern, and the type of energy equations.

We now evaluate the performance of the different dual remote homing algorithms we developed to support integrated loss and delay differentiation. Let e_1 be the energy consumption using the optimal SRH algorithm twice to find two node-disjoint paths with a given hop-constraint. Let e_2 be the energy consumption using the optimal DRH algorithm to find two node-disjoint paths with the same given hop-constraint. We define the *energy benefit ratio*, e to be:

$$e = \frac{(e_1 - e_2)}{e_1}. \tag{13}$$

Given H, the energy benefit ratio of the two algorithms versus hop constraint is given in Fig. 5. In Fig. 5, when h is small, the energy benefit ratio is small. However, the energy benefit ratio increases when allowed number of hops is larger. When the hop-constraint or the network diameter is small, based on the performance graphs we infer that we can use the optimal SRH algorithm (twice) instead of the optimal DRH algorithm in order to get the two node-disjoint paths, since the time complexity of the optimal DRH algorithm is higher than that of the optimal SRH algorithm.

Suppose that each node only has the topology information of k hops beyond itself. We can slightly change the dynamic programming recurrence for the single remote homing algorithm and the dual remote homing algorithm. We report the energy benefit ratio, defined similar to (13), of the solution obtained from the local topology information with the optimal solution obtained from the global topology information for SRH algorithm in Fig. 6. In Fig. 6, H is set to 30, h_1 and h_2 are set to be 10, and k must be no less than 3 to have a feasible solution while using the SRH algorithm. As it shows, when k increases, the energy benefit ratio decreases. When k is 6, the energy benefit ratio is 0. The simulation results show that the dynamic programming based algorithms proposed in this paper work effectively even when only partial topology information is available at each node.

VII. Conclusion

In this paper, we propose optimal remote-homing solutions in order to provide delay and loss differentiation for critical data transmissions in a wireless sensor network. In our solution, each source sensor is assigned one or more remote-homes that are closer to the sink compared to the standard local-home (cluster-head) in the multi-layered information-dissemination tree. By sending critical information to the remote homes, we can achieve lower delay and higher reliability.

We have developed and evaluated dynamic programming optimal algorithms for finding both single remote-homing and dual remote-homing for a given source sensor node in a multi-layered wireless sensor network. We observe that the optimal single remote homing algorithms can be used for effectively providing delay and loss differentiation in smaller wireless sensor networks, and that the dynamic programming based optimal solutions proposed in the paper work effectively even when only local topology information is available.

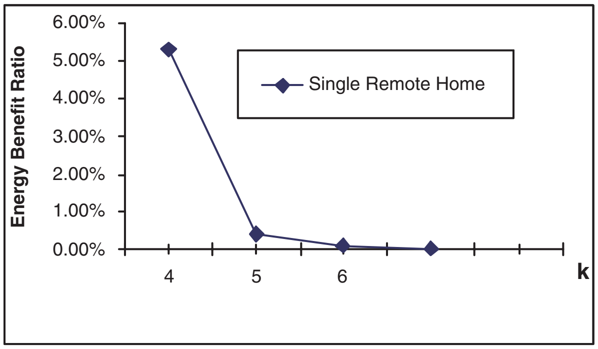

Fig. 6. Energy benefit ratio between global topology information and local topology information for single remote homing.

References

[1] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks,” *IEEE Communications Magazine*, Vol. 40, No. 8, pp. 102-114, Aug. 2002.

[2] J. Ding, K. Sivalingam, R. Kashyapa, and L.J. Chuan, “A multi-layered architecture and protocols for large-scale wireless sensor networks,” *Proceedings of 2003 Vehicular Technology Conference*, pp. 1443-1447, Oct. 2003.

[3] D. Ganesan, R. Govindan, S. Shenker, and D. Estrin, “Highly Resilient, Energy Efficient Multipath Routing in Wireless Sensor Networks,” *Mobile Computing and Communications Review (MC2R)*, vol. 1, no. 2, pp. 1-13, 2002.

[4] S. De, C. Qiao, and H. Wu, “Meshed Multipath Routing with Selective Forwarding: An Efficient Strategy in Wireless Sensor Networks,” *Computer Networks*, vol. 43, no. 4, pp. 481-497, Nov. 2003.

[5] S. De and C. Qiao, “On Throughput and Load Balancing of Multipath Routing in Wireless Networks,” *Proceedings, IEEE WCNC*, pp. 1551-1556, Mar. 2004.

[6] X. Hou, D. Tipper, and J. Kabara, “Label-based Multipath Routing (LMR) in Wireless Sensor Networks,” *Proceedings, The International Symposium on Advanced Radio Technologies (ISART)*, 2004.

[7] B. Deb, S. Bhatnagar, and B. Nath, “ReInForM: reliable information forwarding using multiple paths in sensor networks,” *Proceedings of 28th Annual IEEE International Conference on Local Computer Networks*, pp.406-415, 2004.

[8] B. Deb, S. Bhatnagar, and B. Nath, “Information Assurance in Sensor Networks,” *ACM Workshop on Wireless Sensor Networks*, 2003.

[9] F. Stann and J. Heidemann, “RMST: Reliable Data Transport in Sensor Networks,” *1st IEEE International Workshop on Sensor Net Protocols and Applications (SNPA)*, May, 2003.

[10] S. Narasimhan and S. S. Kunniyur, “Delay Guarantees in Sensor Networks using Power Control,” *Proceedings, Conference on Information Sciences and Systems (CISS’04)*, Mar., 2004.

[11] S. Narasimhan and S. S. Kunniyur, “Effect of Network Parameters on Delay in Wireless Ad-hoc Networks,” *Department of Electrical and Systems Engineering, University of Pennsylvania*, June, 2004.

[12] W. Heinzelman, J. Kulik, and H. Balakrishnan, “Adaptive protocols for information dissemination in wireless sensor networks,” *Proceeding of ACM/IEEE Int’l Conf. Mobile Computing and Networking*, pp. 174-185, Aug. 1999.

[13] A. Manjeshwar and D.P. Agrawal, “TEEN: a routing protocol for enhanced efficiency in wireless sensor networks,” *International Proceedings of 15th Parallel and Distributed Processing Symposium*, pp. 2009-2015, 2001.

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