Data-Centric Routing in Sensor Networks: Single-hop Broadcast or Multi-hop Unicast?

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***Abstract*— Data dissemination strategies and communication protocols that minimize the use of energy can significantly prolong the lifetime of a sensor network. Data-centric dissemination strategies seek energy efficiency by employing short metadata descriptions in advertisements (ADVs) of the availability of data, short requests (REQs) to obtain the data by nodes that are interested in it, and data transmissions (DATA) to deliver data to the requesting nodes. An important decision in this process is whether the DATA transmission should be made at full power in broadcast mode or at low power in multi-hop unicast mode. The determining factor is shown in this paper to be the fraction of nodes that are interested in the DATA, as shown by the number of REQs that are generated. Closed form expressions for this critical fraction of interested nodes is derived when the nodes have no memory or infinite memory for state information and when transmissions are reliable and not reliable. These results can be used during both the design and operation of the network to increase energy efficiency and network longevity.**

***Index Terms*— sensor networks, data-centric, data dissemination, multihop unicast, broadcast**

I. INTRODUCTION

A recent approach to the design of sensor networks utilizes sets of small, low-cost, self-configuring sensor "motes" to monitor environments of interest. Currently available motes cost only a few hundred dollars each and can gather data, run some basic signal processing algorithms, and communicate with each other at distances approaching 150 feet. A typical application scenario involves scattering tens, hundreds or even thousands of these motes over some region to gather data on temperature, humidity, sound, or vibrations.

An important performance goal for such a system is the timely and reliable dissemination of the information they gather and process. This is a challenging goal because these sensor nodes are battery-powered, and it is usually difficult to replace batteries once they are deployed in dangerous or remote locations. Therefore, energy conservation is also an important design consideration for sensor networks.

Many energy-aware routing algorithms [1] [2] have been proposed for the problem of disseminating data in sensor networks. Those routing protocols can be broadly classified as either data-centric or location-centric. Data-centric protocols [4]–[6] use metadata negotiations or named data before any actual data transmissions to eliminate redundant data transmissions, thus achieving energy-efficient dissemination. Location-centric protocols [7] [9] require accurate location information for every sensor node. The query can then be routed to only the interested region, thus reducing the number of transmissions.

We will focus our study on the data-centric routing protocols. Our goal is to provide sensor network designers with tools that help them understand the "3-stage" data-centric protocols in which the motes use 3 different types of messages, ADV, REQ and DATA, to communicate. Our main contribution is an analytical model of and performance evaluation for the energy consumption of a generalized model for these 3-stage data-centric routing protocols. These results then allow us to determine which data dissemination approach, *single-hop broadcast* or *multi-hop unicast*, should be be used in a given network or under a certain set of conditions in that network.

For example, we show that, in all the cases we consider, if the density of the nodes is λ, then multi-hop unicast approach should be chosen when $p < p^*$, where p is the fraction of nodes in the network that are expected to be interested in the data that a node has and p^* is the critical value of p; otherwise, a broadcast approach will use less energy. We show that p^* depends on λ as follows:

$$p^* = \frac{A}{B\lambda} + C \tag{1}$$

The constants in the equation depend on the amount of state information retained at each node, the energy usage profiles of the transmit/receive/idle states of the motes, the fraction of nodes that are sleeping, length of the data packets, the attenuation factor of the channel, etc. This result provides the network designer with a guide on which communication approach is best to use in any given situation.

The rest of the paper is organized as follows. In section II, we provide further motivation for our study. Section III summarizes some data-centric routing protocols. We then generalize, in Section IV, the energy analysis for the 3-stage protocols, and construct models to determine whether it is best to broadcast data with maximum transmission power or to unicast data over multiple hops. We then conclude our paper with summary and description of future work.

II. MOTIVATION

Recent advances in sensor networks have led to many routing protocols specifically designed for resource-constrained sensor motes. A family of data-centric data dissemination protocols is examined in this paper: (a) The SPIN (Sensor

Protocols for Information via Negotiation) protocol family [4] [6] – SPIN-PP, SPIN-EC, SPIN-BC, SPIN-RL; and (b) SPMS (Shortest Path Minded SPIN) [5]. The common idea behind these protocols is to use metadata negotiations or named data before transmitting actual data. Metadata is a high-level data descriptor that is much shorter than the actual data packets and has a one-to-one mapping with the real sensor data. There is no standard metadata format; it is application-specific.

There are three types of messages used in these data dissemination protocols: an ADV message that advertises new data; a REQ message that requests a specific data; and, the DATA message which carries the actual data. ADV and REQ messages contain only metadata. A three-stage (ADV-REQ-DATA) handshaking protocol is then used for data dissemination. The basic protocol begins when a node obtains new data. It sends an ADV message which describes the new data to its neighbors. Upon receiving an ADV, a neighbor node checks to see whether it already possesses the advertised data. If not, it sends a REQ message to the sender. The protocol completes when the sender responds to the REQ with a DATA message. Because only a fraction of the nodes may be interested in the data, this three-stage handshaking mechanism helps remove redundant data transmissions and thus results in more efficient data throughput in resource-constrained sensor networks.

It is well known that radio propagation path loss is a superlinear function of distance. This raises an open problem on how to distribute data to all the interested nodes with minimum energy consumption: one-hop direct broadcast with maximum transmission power or multi-hop unicast with minimum transmission power – or even a hybrid of these two types of delivery. Note that here the underlying assumption is that the network is not partitioned even when the minimum transmission power is used. There exists a trade-off between reaching all nodes in one hop using higher power at a high interference cost and reaching all nodes in multiple hops using less power at a low interference cost. Suppose that the power level of a transmission can be chosen from a set of different values, when is it best to switch from the multi-hop transmissions to direct broadcast if the goal is to minimize energy consumption of the whole network?

Another benefit to using a transmission power that is much smaller than the maximum transmission power is improved network throughput because of a reduction in the media access contentions.

Intuitively, when the network load is low – i.e., only a small fraction of nodes are interested in the data – it is more power efficient to use multi-hop short range communications with minimum transmission power due to the exponential attenuation of radio signals. Conversely, one single-hop broadcast at the maximum transmission power is favorable when the network load is high – i.e., most active nodes are interested in the data – because direct broadcast of the data without metadata negotiations will save the control overhead introduced by the handshaking mechanism. Based on the above discussions, one critical issue in the negotiation-based data dissemination protocol design is to determine the value of the threshold fraction of nodes interested in data beyond which the network should switch from handshaking mechanism to direct broadcasting with maximum transmission power. We will derive an analytical result for this critical fraction of interested nodes in two extreme cases - memoryless case and infinite memory case.

III. DATA-CENTRIC ROUTING PROTOCOLS

Broadcast and unicast are two operations that sensor nodes use to communicate with each other. In this section, we will examine a class of data-centric routing protocols and derive a generalized model for energy analysis.

A. The SPIN Protocol Family

Generally speaking, the family of SPIN protocols are "controlled" flooding protocols. The design goal for the SPIN protocol was to address the "broadcast storms," overlap problems, and resource blindness of traditional flooding protocols.

The SPIN protocol family uses data negotiation and resource-adaptive ideas. Nodes running SPIN perform metadata negotiations before each data transmission. This ensures that no redundant data is transmitted. The SPIN protocol starts with a source broadcasting an ADV message containing metadata for its data. Each node in its transmission range will then respond with a REQ message if it is interested in the data. The DATA is then sent to the interested nodes. The process is recursive; as a result, all the nodes in the network that are interested in the data will eventually receive a copy of it.

SPIN-RL, a variant of SPIN, considers what happens when an ADV or REQ gets lost during transmission. Each node in SPIN-RL keeps track of all the ADVs it has heard, if it does not receive the data within a period of time following a request, the node retransmits the REQ for the data. The resent request can be sent to a different sender since the node may receive the same advertisement from different sources. It then randomly picks from a list of neighbors that had advertised the specific data. If the DATA message is lost, a SPIN-RL node will wait for a predetermined amount of time before responding to any more requests for that piece of data.

B. SPMS

The transmission energy spent in wireless communication is given by a power of the distance between the source and destination. SPIN has no mechanism for adjusting power levels for different transmission distances within one cell. Shortest Path Minded SPIN (SPMS) extends SPIN by using low-power, multi-hop communication for the REQ and DATA messages. A distributed Bellman-Ford algorithm is run to find the shortest paths among all the nodes in a zone, which is defined as a node's coverage area with maximum transmission power. Each node maintains routes to other nodes in the zone. SPMS reduces the energy consumption and delay when compared with SPIN and can be made resilient to intermediate node failures through the use of backup routes.

SPMS divides the whole sensor network geographically into multiple zones based on the sensor nodes' transmission range. As in SPIN, the first phase of SPMS is to broadcast the ADV packet to all its zone neighbors. If a node is interested in the data, it will send a REQ back to the source. In SPIN, a REQ is sent directly to the source in one hop. In SPMS, a REQ packet is sent to the source through the shortest path using the lower possible transmission power for each hop. If a node is not one hop from the source, it has to send its REQ through multiple hops. If a node has to do the multi-hop communications, it will wait for a predetermined fixed time to send out the REQ since the goal is to request data from nodes that are close by and hence can be reached with the minimum use of transmission power. This REQ forwarding process provides the path information to the destination, which enables data from the source to traverse the same path as REQ but in the reverse direction.

Because SPMS is based on multi-hop communications, it experiences the problem that any intermediate node may fail during the communication process. SPMS thus has special mechanisms that account for node failures. At any stage of SPMS, the sink node maintains two routes: best route through **Pr**imary **O**riginator **N**ode (PRONE) and second best route through **Sec**ondary **O**riginator **N**ode (SCONE). There can be multiple SCONES in order to tolerate more node failures. Initially, all nodes set up their PRONE and SCONE to be the source node. If a sink node receives an ADV from a closer node, it will update its PRONE and set SCONE be the PRONE from a previous stage. In a fully connected zone, SPMS can tolerate source node failure after its data has been received by its zone neighbors and tolerate any intermediate node failures during its multi-hop transmissions.

C. Node Failures and Sleep-Wake Strategies

All sensor networks are subject to failure of nodes for many reasons: energy exhaustion, damage, system lock-ups, etc. These failures gradually reduce the density of the nodes. Any strategy for choosing broadcast vs. multi-hop unicast must know how to adapt to this gradual decrease in node density.

To reduce node failures due to energy exhaustion, many networks utilize sleep-wake strategies [3] [8]. For example, at any given time, some fraction of the nodes may be sleeping and are thus out of contact. This also reduces the density of nodes that are able to express interest in an ADV that was just sent. If the sleep time exceeds the time to deliver the data, then it is the same as if the network was operating at a lower density.

For the above reasons, our analysis will incorporate an original density of nodes and allow it to be multiplied by a fraction that specifies the fraction of nodes that are awake when the ADV/REQ/DATA handshakes take place. One consequence of this effect is that a network might need to switch from high-power broadcast to lower-power, multi-hop unicast when the fraction of functioning/awake nodes crosses below a threshold.

IV. DESIGN CHOICES: SINGLE-HOP BROADCAST OR MULTI-HOP UNICAST

Our goal is to determine which approach - single-hop broadcast or multi-hop unicast - minimizes energy usage in any specified situation. Sensor nodes are distributed in a zone Z according to a Poisson process with rate λ. Each node decides independently with probability p whether it is interested in the advertised data. The nodes interested in the data are therefore distributed according to a Poison process with rate $p\lambda$.

We will show that which approach is better depends on the fraction of the nodes in the network that are interested in the data. There is a critical value of p, say p^*, such that we should use multi-hop unicast whenever $p \leq p^*$, and broadcast otherwise. In all cases, we find that p^* is related to λ by Eq. (1).

Determining p^* for protocols where each node only has finite memory used to cache the requests and data is difficult due to the complexity of cache management, so we determine lower and upper bounds for any real protocol. The upper bound will be obtained by assuming that all nodes retain all information that they hear: the *infinite memory* case. The lower bound will correspond to a network in which nodes do not remember any information: the *memoryless* case.

Assumptions: (i) Nodes are uniformly distributed in a circle with a density of λ nodes per unit area; (ii) There are k different transmission power levels, varying from a minimum radius r_1 (=r) to a maximum radius r_k (=$k \times r$); (iii) The nodes around a node broadcasting an ADV can be considered to be divided into non-overlapping rings of width r; (iv) A packet can always get from one ring to the next in one hop; (v) The received signal power is proportional to $r^{-\alpha}$, where r is the distance from the transmitter and $2 \leq \alpha \leq 4$; and (vi) The fraction of nodes that are functioning/awake is β.

A. The Case of Failure-Free Transmissions

Since the rings do not overlap, the number of the nodes in each ring is independent. Let N_i be the number of nodes in ring i that are interested in the data. Assume that the fixed energy costs associated with radio setup in transmit mode and receive mode are $\mathcal{E}_s$ and $\mathcal{E}_r$ respectively. The energy required to broadcast data to the entire zone is the sum of the transmission energy broadcasting at maximum transmission power plus the energy used by all the nodes in the network to listen to the broadcast:

$$\mathbb{E}[\mathcal{E}_b] = c_1(kr)^\alpha PL_d + \mathcal{E}_s + \mathbb{E}[\mathbf{N}](c_2 PL_d + \mathcal{E}_r) \tag{2}$$

where $\mathbb{E}[\mathbf{N}] = \beta\lambda\pi(kr)^2$ is the expected number of nodes that are interested in the data.

The energy cost of sending a packet with payload PL over one hop is given by:

$$\mathcal{E}_s^1 = c_1 r^\alpha PL + \mathcal{E}_s \tag{3}$$

where c_1 is the energy cost per bit sent.

In a similar fashion, the energy cost of receiving a packet with payload PL over one hop is given by:

$$\mathcal{E}_r^1 = c_2 PL + \mathcal{E}_r \tag{4}$$

Assume that the size of ADV and REQ packets is PL_c bits and the size of data packets is PL_d bits, including the MAC layer overhead.

The energy required to move data one hop is the energy required to transmit and receive one ADV and one REQ plus the energy required to transmit and receive one data packet:

$$\mathcal{E}_{hop} = c_1 r^{\alpha}(2PL_c+PL_d)+3\mathcal{E}_s+c_2(2PL_c+PL_d)+3\mathcal{E}_r \quad (5)$$

1) Memoryless Case: First consider the worst case in which each request is handled separately because any intermediate node cannot cache the request. The request goes from the sink to the source and data moves from the source to the sink. The total energy consumption in this memoryless case is given by the number of hops required to reach each node that is interested times the energy used per hop:

$$\mathcal{E}^0_{mh} = (\mathbf{N}_1 + 2\mathbf{N}_2 + \cdots + k\mathbf{N}_k)\mathcal{E}_{hop} \quad (6)$$

The total expected energy is thus:

$$\mathbb{E}[\mathcal{E}^0_{mh}] = (\mathbb{E}[\mathbf{N}_1] + 2\mathbb{E}[\mathbf{N}_2] + \cdots + k\mathbb{E}[\mathbf{N}_k])\mathcal{E}_{hop} \quad (7)$$

The expected number of interested nodes in each ring is given by:

$$\mathbb{E}[\mathbf{N}_i] = (\pi(ir)^2 - \pi((i-1)r)^2)p\beta\lambda \quad (8)$$

From (7) and (8),

$$\mathbb{E}[\mathcal{E}^0_{mh}] = \frac{1}{6}\mathcal{E}_{hop} p\beta\lambda\pi r^2 k(k+1)(4k-1) \quad (9)$$

For the k-hop case, the power used by broadcast and unicast are equal when:

$$\begin{aligned}\frac{1}{6}\mathcal{E}_{hop} p^*_0 \beta\lambda\pi r^2 k(k+1)(4k-1) = \\ c_1(kr)^{\alpha} PL_d + \mathcal{E}_s + \mathbb{E}[\mathbf{N}](c_2 PL_d + \mathcal{E}_r)\end{aligned} \quad (10)$$

Solve (10) for p^*_0,

$$p^*_0 = \frac{6(c_1(kr)^{\alpha} PL_d + \mathcal{E}_s + \mathbb{E}[\mathbf{N}](c_2 PL_d + \mathcal{E}_r))}{\mathcal{E}_{hop}\pi r^2 \beta\lambda k(k+1)(4k-1)} \quad (11)$$

2) Infinite Memory Case: Assume that each node has infinite memory so that it can cache all overheard requests and data. This is the best case scenario. Each node perceives all data as coming from sources that are one-hop neighbors. Thus:

$$\mathcal{E}^{\infty}_{mh} = (\mathbf{N}_1 + \mathbf{N}_2 + \cdots + \mathbf{N}_k)\mathcal{E}_{hop} \quad (12)$$

The total expected energy is thus:

$$\mathbb{E}[\mathcal{E}^{\infty}_{mh}] = p\beta\lambda\pi(kr)^2\mathcal{E}_{hop} \quad (13)$$

$$p^*_{\infty}\beta\lambda\pi(kr)^2\mathcal{E}_{hop} = c_1(kr)^{\alpha} PL_d + \mathcal{E}_s + \mathbb{E}[\mathbf{N}](c_2 PL_d + \mathcal{E}_r) \quad (14)$$

Solving Eq. (14) for p^*_{∞},

$$p^*_{\infty} = \frac{c_1(kr)^{\alpha} PL_d + \mathcal{E}_s + \mathbb{E}[\mathbf{N}](c_2 PL_d + \mathcal{E}_r)}{\beta\lambda\pi(kr)^2\mathcal{E}_{hop}} \quad (15)$$

Notice that p^* for both cases has the form $p^* = \frac{A}{B\lambda} + C$. The behavior of p^* for different values of λ, k, and α is shown in Fig. 1-3. The parameters are $\pi r^2 = 1$, $\beta = 1$, $c_1 = 0.67\pi^{\alpha/2}\mu J/bit$, $c_2 = 0.68\mu J/bit$, $\mathcal{E}_s = 46.5\mu J$, $\mathcal{E}_r = 47.1\mu J$, $PL_d = 21PL_c$, $PL_c = 96$ bits. The parameters are calculated using the specs of Mica2 motes. For a given curve, if the fraction of the interested nodes satisfies $p \leq p^*$, then we should choose multi-hop unicast transmission over direct broadcast. Notice that in Figure 1, p^* increases as the number of hops k increases in the infinite memory case because the energy cost of going far off via unicast does not increase with k due to cached requests and data by intermediate nodes. Figure 2 shows that p^* increases as α increases, which indicates that multihop unicast communication is favored in non LOS propagation. Notice that in Figure 3, for $\alpha = 4$ (non LOS, two path model for large distances), p^* eventually begins increasing as a function of the number of hops in the zone.

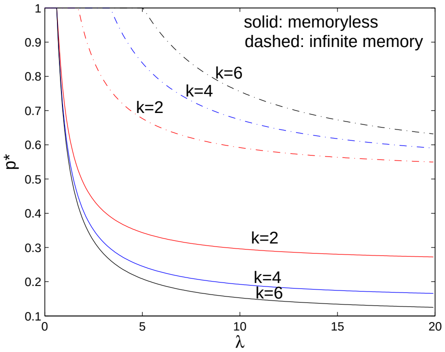

Fig. 1. The critical fraction of interested nodes vs. the node density λ as the number of hops k is varied ($\alpha = 3$)

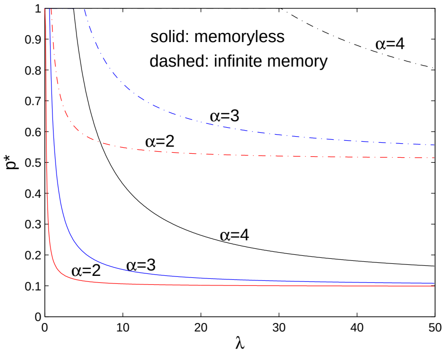

Fig. 2. The critical fraction of interested nodes vs. the node density λ as α is varied ($k = 6$)

B. *The Case of Transmissions with Failures*

Retransmissions due to node or link failures could increase the energy cost. Suppose the probability of transmission failure is q. Let A_i be the number of transmission attempts required for node i to receive a packet successfully.

$$P(A_i \leq n) = 1 - q^n \quad (16)$$

where $n = 1, 2, 3, \cdots$

$$\mathbb{E}[A_i] = \frac{1}{1-q} \quad (17)$$

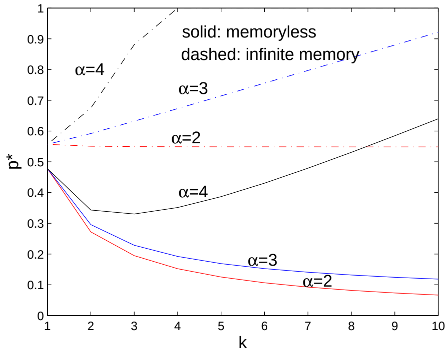

Fig. 3. The critical fraction of interested nodes vs. the number of hops, k , as α is varied ($\lambda = 10$)

If an intermediate node keeps transmitting until successful and each transmission is independent, the expected number of transmissions for the receiver to get the packet correctly is $k/(1-q)$.

The packet loss probability is q_b for the broadcast, assuming each node receives the broadcast packet independently. Probability that all nodes get the packet within n attempts is as follows:

$$P(A \leq n) = \prod_{i=1}^{N} P(A_i \leq n) = (1 - q_b^n)^N \tag{18}$$

where $N = \beta\lambda\pi(kr)^2$.

$$\begin{aligned} \mathbb{E}[A] &= \sum_{n=1}^{\infty} nP(A = n) = \sum_{n=1}^{\infty} P(A \geq n) \\ &= \sum_{i=1}^{N} (-1)^{i+1} \binom{N}{i} \frac{1}{1 - q_b^i} \end{aligned} \tag{19}$$

The expected energy usage for broadcasting to ensure that every node in the zone receives the packet is then:

$$\begin{aligned} \mathbb{E}[\mathcal{E}_{bc}] = (c_1(kr)^\alpha PL_d + \mathcal{E}_s + N(c_2 PL_d + \mathcal{E}_r)) \\ \sum_{i=1}^{N} (-1)^{i+1} \binom{N}{i} \frac{1}{1 - {q_b}^i} \end{aligned} \tag{20}$$

1) Memoryless Case: The total expected energy for the memoryless case, given that the unicast transmission failure probability is q:

$$\begin{aligned} \mathbb{E}[\mathcal{E}_{mh}^0] &= (\mathbb{E}[\mathbf{N}_1]\frac{1}{1-q} + \cdots + \mathbb{E}[\mathbf{N}_k]\frac{k}{1-q})\mathcal{E}_{hop} \\ &= \frac{\mathcal{E}_{hop} p\beta\lambda\pi r^2 k(k+1)(4k-1)}{6(1-q)} \end{aligned} \tag{21}$$

Equating the right sides of (20) and (21), and solving for the critical p_0^* yields:

$$p_0^* = \frac{6(1-q)\mathbb{E}[\mathcal{E}_{bc}]}{\beta\lambda\pi r^2 k(k+1)(4k-1)\mathcal{E}_{hop}} \tag{22}$$

2) Infinite Memory Case: The total expected energy for the infinite memory case given that the unicast transmission failure probability is q:

$$\begin{aligned} \mathbb{E}[\mathcal{E}_{mh}^\infty] &= (\mathbb{E}[\mathbf{N}_1]\frac{1}{1-q} + \cdots + \mathbb{E}[\mathbf{N}_k]\frac{1}{1-q})\mathcal{E}_{hop} \\ &= \frac{p\beta\lambda\pi(kr)^2}{(1-q)}\mathcal{E}_{hop} \end{aligned} \tag{23}$$

Equating the right sides of (20) and (23), and solving for the critical p_∞^* yields:

$$p_\infty^* = \frac{(1-q)\mathbb{E}[\mathcal{E}_{bc}]}{\beta\lambda\pi r^2 k^2 \mathcal{E}_{hop}} \tag{24}$$

The behavior of the critical probability in these cases of transmission failures is generally the same as in the failure free case - the failure probabilities shift the curves up(right) or down(left).

V. CONCLUSION AND FUTURE WORK

We have performed an energy efficiency analysis and given closed-form results for the worst-case and best-case scenarios. In these two cases we are able to calculate the critical value for the fraction of nodes interested in the data at which the switch should be made between one-hop broadcast communication with maximum transmission power and multi-hop unicast communication with minimum transmission power.

Cases that arise in practice will lie between these extreme cases. We thus wish to develop very realistic analytical models that account for the way information is disseminated in a real network. This would, for example, require that we model the spatial process that describes how both REQs and DATA messages propagate through the network when nodes have large memories and omnidirectional and/or directional antennas. The challenge in this case is modeling the way in which one node that would like to request the data can overhear another node's request – and then hold its request and wait to overhear the DATA when it is sent to the first node.

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