Distance-Based Routing for Balanced Energy Consumption in Sensor Networks

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***Abstract*—In sensor networks, data traffic is concentrated towards a small number of base stations, and those nodes close to the base station have to relay large amount of data for the rest of the network. This would deplete the batteries of these nodes very quickly, and reduce the network lifetime. In order to alleviate this problem, a novel solution is proposed in this paper, where the transmission powers of the nodes in the network are determined based on their distance from the base station. This solution promises to balance the energy consumption in the network without periodically collecting network state information or using nodes with special capabilities. The optimal affine distance-based routing strategy is analytically determined, and it is shown that the proposed method can increase the network lifetime by more than twice of that in a network employing minimum energy routing scheme with constant transmission ranges. Finally, the optimal transmission ranges of the nodes are characterized with respect to the network size and the energy costs due to transmit amplifier and transceiver electronics.**

I. Introduction

The motivation for our work stems from the observation that in a sensor network, sensor nodes closer to the base station (BS) have to forward more packets than the ones at the periphery of the network. The increase in the amount of data forwarded usually translates into increase in the energy consumption when everything else is kept the same[1]. Therefore, the nodes close to the BS die first, leading to a premature loss of connectivity in the sensor network. Note that this effect occurs regardless of the routing strategy, MAC layer, physical layer considerations, etc., that are currently investigated in the literature. In order to alleviate this undesirable effect, there have been several proposals ranging from using mobile base stations [2] to using nodes with multiple levels of batteries placed concentrically around the base station [4]. However, these solutions require re-design of the network nodes (either the BS or the sensor nodes), and are not applicable to homogeneous sensor networks with all nodes having similar specifications. There are also some routing strategies that aim to balance the load in the network by using routing metrics taking into account the *residual energy* of the nodes [8]. However, these routing algorithms can perform arbitrarily bad, if they do not have accurate residual energy capacity information of the nodes in the network. Obtaining accurate network state information in terms of residual energies of the nodes requires continuous and periodic updates throughout the network. This update also consumes energy, and may obliterate the benefits provided by the routing algorithm.

[1]This is a reasonable assumption if one of the many proposals in the literature minimizing the idle energy consumption, e.g., [5] is used.

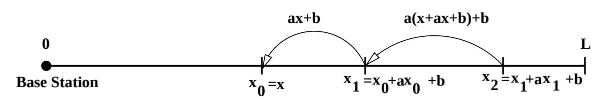

Fig. 1. Linear network topology.

In this work, we propose a much simpler routing strategy for balancing the energy consumption, which is suitable for homogeneous networks, and does not require the current network state information for correct operation. Our proposed strategy relies on adjusting the transmission powers of the nodes based on their distance from the BS. Intuitively speaking, the load of the nodes can be more balanced if the nodes closer to the periphery of the network transmit with higher transmission powers than the nodes located closer to the BS. As demonstrated later in the paper, by this way, transmission energy costs of nodes closer to the BS decrease not only due to the lower transmission powers, but also due to the lower number of packets relayed by those nodes. The most important advantage of distance-based routing strategy proposed in this paper is that the routing strategy in terms of the transmission powers of the nodes remains the same throughout the duration of the network lifetime. In other load-balancing routing schemes, continuous update of the routes based on the residual energy of the nodes is required. Thus, our proposed strategy reduces the cost of managing the network significantly compared to the previous approaches. The algorithm only requires the localization of the sensor nodes, which can be provided by one of the many localization algorithms proposed in the literature, e.g., [9].

The paper is organized as follows. In Section II, we present the system model considered in the paper. In Section III, we summarize the minimum energy routing algorithms previously proposed in the literature. Our proposed optimization model and its analytical solution is discussed in Section IV. We investigate the characteristics of the optimal solution by numerical studies in Section V, and conclude with Section VI.

II. System Model

In order to have a tractable analysis, we consider a continuum of nodes distributed on a line, and one base station (BS) is located at the left-most position as shown in Figure

1. This case is obviously a simplification, but it constitutes an important special case of more general two-dimensional networks. Linear networks were considered in many other previous works (e.g., [6], [7]). The continuum node assumption was also previously considered in the literature (e.g., [10], [11]). The continuum node assumption is used to determine the exact optimal locations of the relay nodes, and thus, provides a lower bound on the performance of the proposed algorithm. The distance between the BS and the furthest node is L units. Without loss of generality, we designate each node with its distance from the BS. For example, the distance between the BS and node x is x units. Sensor nodes sense the environment and generate data that needs to be forwarded to the BS. They also act as relays for their *upstream nodes*[2]. We adopt the radio model considered in [1], i.e., the power required by a relay node to transmit a bit of data to a distance d is given by

$$P(d) = P_c + P_t d^{\alpha}, \tag{1}$$

where α is the path loss coefficient, and P_c and P_t correspond to the unit circuit and amplifier energy consumption, respectively. We assume that the network is homogeneous, i.e., the physical characteristics of the nodes are the same, and nodes generate data at a rate 1 bits per second.

III. Minimum Energy Routing

The simplest way of communication between nodes and the BS is over a direct link. Using direct transmission, each node sends its data directly to the BS, and no other node is involved in the transmission process. With direct transmission, the batteries of the nodes far away from the base station will quickly drain since the transmission power increases exponentially with the transmitted distance. Another approach is to use other intermediate nodes as relays. Multi-hop routing is preferable to direct transmission for long-haul transmissions, since it can dramatically reduce the transmission power compared to direct transmissions. Although employing multi-hop transmissions reduces the energy consumption of the nodes far away from the BS, it increases the energy consumption of intermediate nodes. In [1], the authors investigated the problem of finding the optimal number of relays and their locations in the network, so that the total relaying energy is minimized. In particular, the authors solve the following optimization problem (P).

$$\begin{aligned}(P) \ \ \min \sum_{i=1}^{K} & P_c + P_t d_i^{\alpha} \\ \sum_{i} & d_i \geq D,\end{aligned} \tag{2}$$

where d_i is the distance between the $i-1$th and ith relay nodes, and K is the number of hops between the source and the destination. Assuming only a single route is active in a multihop network, it is shown in [1] that when the relay nodes are separated by the so called *characteristic distance*, i.e., $d_{char} = \sqrt[\alpha]{\frac{P_c}{P_t(\alpha-1)}}$, then the total relaying energy over that route is minimized. Thus, the optimal number of hops, K_{opt}, required to transmit data from a node D meters away from the BS is given by $\left\lceil \frac{D}{d_{char}} \right\rceil$. However, this solution does not take into account the cumulative transmission energy consumed by relay nodes for carrying data incoming from their upstream nodes. We observe that as data traffic is concentrated towards a base station, the sensor nodes around the base station have to forward data for other nodes whose number can be very large; this problem always exists, regardless of what energy conserving protocol is used for data transmission.

IV. Distance-based Routing

In this work, we propose a general *routing* framework for balancing the energy consumption in the network. In this framework, the transmission range of each node is a function of its distance from the BS. In particular, node x is the relay node for node $x + f(x)$; node $x + f(x)$ is the relay for node $(x + f(x)) + f(x + f(x))$; and so on. Our hypothesis is that by appropriately varying the transmission ranges of the nodes based on their distance from the BS, we can balance the energy consumption in the network. In order to prove our hypothesis, we assume that $f(x)$ is an affine function, i.e., $f(x) = ax + b$, where a and b are real scalars. Analysis of more general functions is left as a future work. Therefore, if $a > 0$, then the transmission range of nodes far away from the BS increases, and if $a < 0$, the transmission range of those nodes decreases. Also, the case $a = 0$ is a special case where the transmission ranges of the nodes are the same, and it mimics the scenario considered in [1]. For example, Figure 1 depicts the increase in transmission ranges of the upstream nodes of x when $a > 0$. Clearly, different types of functions can be used as $f(x)$, e.g., strictly concave or convex functions. The evaluation of the optimality conditions of other types of functions is left as a future work.

In order to determine the best affine function to be used for routing, we derive the following properties.

Property 1: Let $K(x)$ be the number of upstream nodes for which node x acts as a relay node. For $a > 0$, an upper bound on $K(x)$ is given as

$$K(x) \leq \frac{\log(L + b/a)}{\log(1+a)} - \frac{\log(x + b/a)}{\log(1+a)}. \tag{3}$$

Proof The number of upstream nodes for which node x acts as a relay node for given a and b can be calculated through a recursion. It is important to note that the energy consumed by a node increases linearly with the number of nodes for which it acts as a relay node. As shown in Figure 1, node $x_0 = x$ is the relay node for node $x_1 = x_0 + ax_0 + b$. Therefore, node x_0 forwards not only the data generated by itself but also the data incoming from node x_1. In a similar fashion, node x_1 acts as a relay for node $x_2 = x_1 + ax_1 + b$. In general, node x is the relay for all nodes $x_k = x_{k-1} + ax_{k-1} + b$, $k = 1, \ldots, K(x)$, where $K(x)$ is such that $x_{K(x)+1} > L$ and $x_{K(x)} \leq L$. Therefore, $K(x)$ represents the maximum number of nodes for which x

[2] For node x, all nodes with index less than x are called downstream nodes, and all nodes with index greater than x are called upstream nodes.

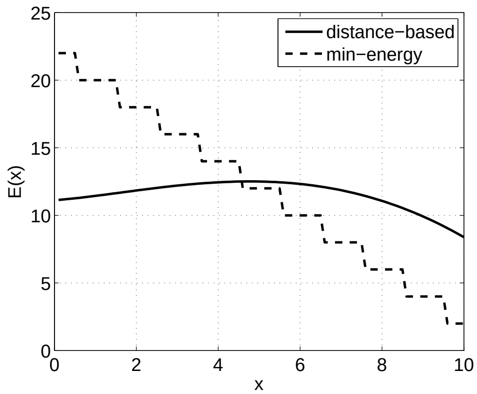

Fig. 2. Energy consumption of nodes, $E(x)$ with distance-based routing and minimum energy routing when $a = 0.2359, \alpha = 2, P_c = P_t = 1$.

acts as a relay node. Since all nodes in the network generate data packets, node x forwards $K(x) + 1$ packets in total.

In order to determine $K(x)$, we solve the aforementioned recursion. The first few steps of the recursion are given as follows:

$$
\begin{aligned}
x_1 =& x_0 + ax_0 + b = (1+a)x_0 + b,\\
x_2 =& x_1 + ax_1 + b = (1+a)^2 x_0 + (1+a)b + b,\\
x_3 =& x_2 + ax_2 + b\\
=& (1+a)^3 x_0 + (1+a)^2 b + (1+a)b + b,\\
&\vdots
\end{aligned}
$$

In general,

$$x_k = (1+a)^k x_0 + b \sum_{i=0}^{k-1} (1+a)^i. \tag{4}$$

For $a \neq 0$,

$$x_k = (1+a)^k x_0 + \frac{b}{a}\left[(1+a)^k - 1\right]. \tag{5}$$

$K(x)$ is calculated by using the inequality $x_{K(x)} \leq L$. After some algebra, the upper bound on the number of nodes for which x acts as a relay node is calculated as in (3). ■

Note that if $a = 0$, all nodes have the same transmission range. In this case, the closest upstream node of x that forwards data to x is located at $x+b$, the second closest is located at $x + 2b$, and so on. Thus, the number of nodes for which node x is a relay node is simply given by $K_0(x) \leq \lceil \frac{L-x}{b} \rceil$.

Property 2: Let $E(x)$ be the cumulative energy consumed by node x in order to forward data generated by itself and by its upstream nodes. An upper bound on $E(x)$ is given as

$$
\begin{aligned}
E(x) \leq & \left[\frac{\log(L + b/a)}{\log(1+a)} - \frac{\log(x + b/a)}{\log(1+a)} + 1\right]\\
& \times \left[P_t \left(\frac{ax+b}{1+a}\right)^\alpha + P_c\right].
\end{aligned} \tag{6}
$$

Proof The energy cost of node x depends on the number of packets it relays, and its transmission range. Note that there exists another node $x' > 0$ which acts as a relay for node x. The distance between node x and x' is $ax' + b$. Therefore, $x' = \frac{x-b}{1+a}$. The transmission range of node x is given by $d = x - x' = \frac{ax+b}{1+a}$. By definition, the unit energy consumed to forward data from x to x' is given by

$$P\left(\frac{ax+b}{1+a}\right) = P_t\left(\frac{ax+b}{1+a}\right)^\alpha + P_c.$$

Thus, the cumulative energy consumed by node x in order to forward data generated by itself and by its upstream nodes is

$$E(x) = [K(x) + 1]P\left(\frac{ax+b}{1+a}\right). \tag{7}$$

Inserting (3) in (7), we get the desired result. ■

Among all nodes in the network $0 < x \leq L$, there exists at least one node x^* for which $E(x^*)$ is the maximum. For example, when $a = 0$, as demonstrated in Figure 2, the node with the maximum energy consumption is the node that is the closest to the BS. In order to prolong the lifetime of an energy-constrained sensor network, our objective is to minimize $E(x^*)$ by selecting appropriate values for a and b. This would balance the energy consumption in the network, and thus, increase the network lifetime. Therefore, we investigate the solution of the following optimization problem

$$(Q) \quad \min_{a,b}\left[\max_x E(x)\right]$$

Let $W(u) = v$ evaluate $v\exp(v) = u$ for v as a function of u. $W(u)$ is also called Lambert-W or omega function [3]. Then, we can state the following lemma for finding the local extremum for $E(x)$.

Lemma 1: The local maximizer for $E(x)$ is calculated as $x^* = \exp(z^*) - \frac{b}{a}$, where

$$
\begin{aligned}
z^* =& \frac{1}{\alpha} W\left(\frac{-P_c}{P_t\left(\frac{a}{1+a}\right)^\alpha}\exp(1 - \alpha\log(L + b/a))\right)\\
& + \frac{1}{\alpha}\left(-1 + \alpha\log(L + b/a)\right).
\end{aligned} \tag{8}
$$

Proof The function $E(x)$ is not concave for all possible values of a and b. A necessary condition for $E(x)$ to be a concave function is determined by observing the second derivative of $E(x)$. After some straightforward algebra, it can be shown that $E(x)$ is a concave function if the following condition is satisfied when $a > 0$:

$$\frac{P_c}{P_t}\left(\frac{1+a}{b}\right)^\alpha + \alpha(\alpha-1)\log\left(\frac{aL+b}{b}\right) < 2\alpha - 1. \tag{9}$$

We determine a local maximizer for $E(x)$ by considering the first order optimality conditions, i.e., $\frac{\mathrm{d}E}{\mathrm{d}x} = 0$. The first derivative of $E(x)$ is given as:

$$
\begin{aligned}
\frac{\mathrm{d}E}{\mathrm{d}x} =& -P_c +\\
& P_t\left(\frac{a}{1+a}\right)^\alpha \exp(\alpha z)\left[-1 + \alpha\log\left(L + \frac{b}{a}\right) - \alpha z\right],
\end{aligned}
$$

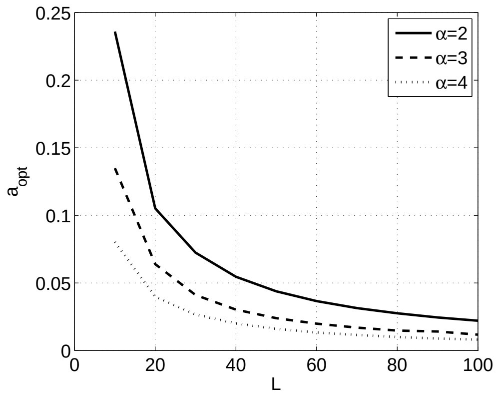

Fig. 3. Optimal values of a for varying L when $P_c = P_t = 1$.

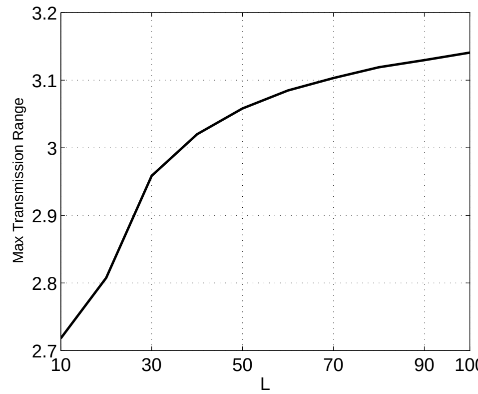

Fig. 4. Maximum transmission ranges of the nodes for varying network sizes L when $\alpha = 2, P_c = P_t = 1$.

where $z = \log(x + b/a)$. The root of this equation, z^*, is calculated as in (8). ■

Once the maximum value for $E(x)$ is calculated according to (8), the optimization problem (Q) is solved numerically, wherein we assume that $b = d_{char}$. We consider this value for b in order to revert to the case in [1] when $a = 0$. The solid line in Figure 2 depicts the energy consumed per node with distance-based routing when $L = 10$, $\alpha = 2$ and $P_c = P_t = 1$. For this case, the optimal value of a, denoted as a_{opt}, is calculated as 0.2359. As depicted in the figure, the maximum energy consumed with our proposed scheme, is approximately 50% less than the maximum energy consumed with fixed transmission ranges. Also, it is interesting to note that the node that has the maximum energy consumption is closer to the center of the network, and a large portion of the nodes in the network have similar energy consumption. Therefore, the energy consumption in the network is much more balanced when the distance-based routing scheme is used.

V. Numerical Analysis

In this section, the optimal transmission ranges with the distance-based routing scheme is characterized for varying network conditions. We first depict the variation of a_{opt} for varying network sizes in Figure 3. Note that as the network size gets larger, the optimal value, a_{opt}, gets smaller. Therefore, the maximum transmission range does not change significantly with respect to the size of the network. This observation is better illustrated in Figure 4, where the variation of the maximum transmission range of the nodes for varying network size is given. It is interesting to note that for small networks, the maximum transmission range is almost a quarter of the length of the network. However, as the network size increases, this ratio reduces almost 3% of the length of the network. It is also observed in Figure 3 that as the path loss coefficient increases, the importance of changing the transmission range with respect to the location becomes less important.

In Figure 5, the variation of a_{opt} with respect to P_t/P_c is given. As P_t/P_c increases, the energy consumption with respect to the transmit amplifier becomes more dominant compared to the energy consumption in the transceiver electronics. For this case, we also observe that a_{opt} decreases with increasing P_t/P_c, but the decrease is not as significant as observed in Figure 3. Note that when high energy is consumed in the transmit amplifier, increasing the transmission range would also increase the total energy consumption, and thus, relaying with lower transmission power is preferred.

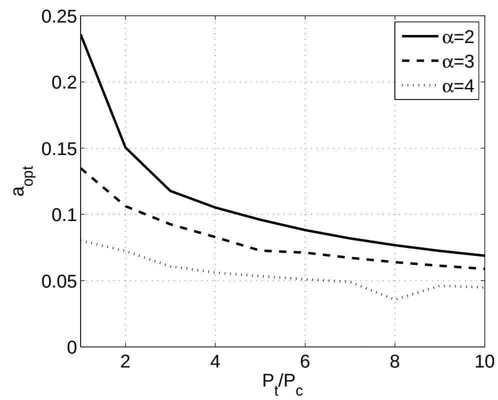

Fig. 5. Optimal values of a for varying P_t/P_c when $L = 10$.

In Figure 6, the transmission ranges of the nodes in the network is depicted with respect to the locations of the nodes. It is interesting to note that the transmission ranges of the nodes at the periphery of the network are much higher than those of the nodes close to the BS. In the optimal solution, the node that is furthest away from the BS has a transmission range approximately four times higher than the characteristic distance d_{char}. Moreover, the transmission ranges decrease linearly as we approach the BS. The optimality of this result is quite intuitive, since those nodes closer to the BS has to carry more data, and in order to balance the energy consumption, they transmit with lower transmission power.

Figure 7 shows that when distance-based routing strategy is used, the number of packets carried by the nodes in the network decreases significantly as compared to the case when each node has the same transmission range d_{char}.

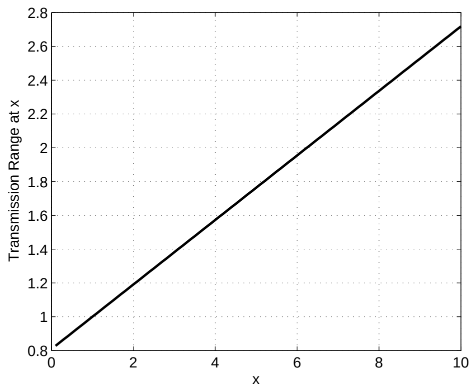

Fig. 6. Transmission ranges of the nodes with distance-based routing when $a = 0.2359, \alpha = 2, P_c = P_t = 1$.

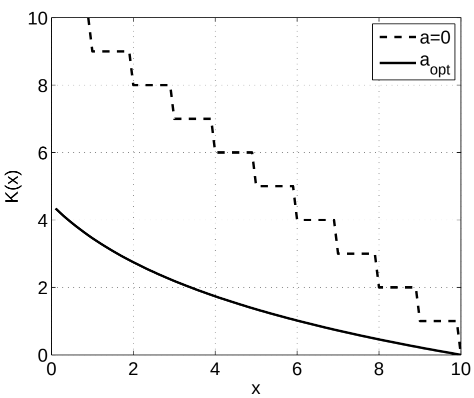

Fig. 7. Number of packets forwarded by each node in the network when $a_{opt} = 0.2359, \alpha = 2, P_c = P_t = 1$.

Finally, we investigate the delay performance of distance-based routing scheme. For this purpose, we determine the number of hops a packet from node x takes to reach the BS. As demonstrated in Figure 8, the nodes can reach the BS in significantly fewer number of hops when compared to the routing with optimal constant transmission range. Thus, our proposed routing scheme not only balances the energy consumption, but also decreases the average delay in terms of the average number of hops in the network.

VI. Conclusions and Future Extensions

In this paper, we proposed a new routing framework to balance the energy consumption in wireless sensor networks when the nodes forward their collected data to a single base station. Our proposed method differs from the previous work in the way that it can be implemented in homogeneous networks without requiring nodes with special capabilities. Furthermore, as long as the location of the node in the network does not change, its transmission range remains the same for the duration of the network lifetime. This eliminates any need to collect up-to-date residual energy information as required in other previously proposed routing algorithms in the literature.

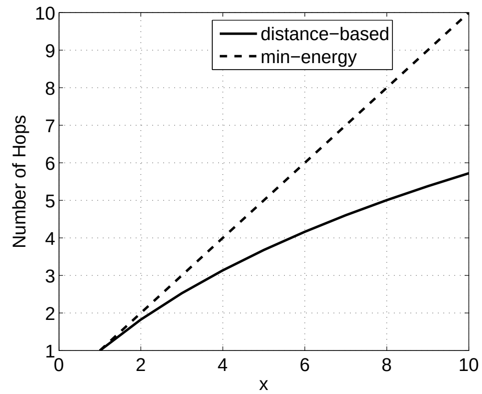

Fig. 8. Number of hops vs. distance of the node from the BS when $L = 10, \alpha = 2, P_t = P_c = 1$.

In this work, we presented the best routing strategy in terms of total expanded energy when all transmissions are reliable. However, the reliability of transmissions depend on the rates of the transmissions, noise and interference on the channel. In addition, the spatial reuse is important in multi-hop wireless networks whereby the terminals are allowed to transmit simultaneously, so as to increase the end-to-end throughput. As future work, we plan to extend our results taking into account these issues for two-dimensional networks, and investigate if a convex function $f(x)$ can better balance the network.

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