QoS and Energy-Aware Dynamic Routing in Wireless Multimedia Sensor Networks

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***Abstract*—The increasing availability of low-cost hardware along with the rapid growth of wireless devices has enabled the development of Wireless Multimedia Sensor Networks (WMSNs). Multimedia content such as video and audio streaming is transmitted over a WMSN which can easily be deployed with low cost. However, enabling real-time data applications in those networks demands not only Quality of Service (QoS) awareness, but also efficient energy management. Sensor network devices have limited energy resources. The limited energy poses significant threats on the QoS of WMSNs. In this paper, to improve the efficiency of QoS-aware routing, we examine an angle-based QoS and energy-aware dynamic routing scheme designed for WMSNs. The proposed approach uses the inclination angle and the transmission distance between nodes to optimize the selection of the forwarding candidate set and extend network lifetime. Simulation results indicate that considerable lifetime values can be achieved.**

I. Introduction

Wireless Sensor Networks (WSNs) have great potential for a wide variety of applications, such as remote environmental monitoring, target tracking and traffic control [1]. Inch-scale and low-cost sensor devices can measure temperature, humidity, or find the location of objects. In recent years, research advancements have also made available inexpensive CMOS cameras and microphones that can capture multimedia content. The low cost of multimedia hardware has fostered the development of Wireless Multimedia Sensor Networks (WMSNs) [2]. Consequently, the research interest in WSNs has shifted from measuring physical phenomena to enabling multimedia delivery such as video and audio streams over sensor networks.

A WMSN is a network of wireless interconnected smart devices that enables retrieving video and audio streams. The devices usually operate autonomously on limited non-rechargeable battery power and are expected to last for several months or even years. Therefore, a major concern is to improve the energy efficiency of the network and maximize node lifetime. However, the unique characteristics of WMSNs pose significant challenges on the problem of energy efficiency. Most multimedia applications produce high volumes of data and require high transmission rates while sensor nodes are battery-constrained devices. Maximizing the lifetime of those networks is a critical issue.

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In parallel with the optimal energy management issue, there also exists the demanding requirement of adequate communication-wise operation and performance of the WMSNs. Most potential applications of WMSNs have predetermined levels of Quality of Service (QoS). QoS is the ability to deliver a guaranteed level of service to applications [3]. Existing work that exploits multipath routing to extend network lifetime suffers from increased delay.

QoS routing is an important research issue in WMSNs. This work considers a QoS and energy-aware routing protocol designed to extend network lifetime while guaranteeing delay QoS constraints. The impact of the selection of a proper forwarding candidate set in an Angle-based Dynamic Routing Scheme (ADRS) [4] is examined. Then, a scheme that properly selects the forwarding candidate set in order to optimize the lifetime under QoS constraints is introduced. The scheme is also compared with a simple routing scheme that follows the shortest-path approach.

This work addresses two important issues of multiconstrained QoS routing in WMSNs: 1) How important is the forwarding candidate set selection on the network lifetime and what is the optimal candidate set? 2) Under certain QoS constraints and node transmission range, can a proper packet transmission mechanism extend the network lifetime?

The major contributions of this work are listed below:

- We provide an analytical evaluation of the impact of the selection of the forwarding candidate set on the network lifetime. Especially, we explore the effect that the choice of the forwarding area has on the network lifetime.
- We propose to use the ADRS in order to improve the network lifetime, network reliability and packet latency.
- Through comprehensive performance evaluation, we demonstrate the efficiency of the proposed scheme and we compare it with other approaches.

The remainder of the paper is structured as follows: Section II reviews the related work, the network model is presented in Section III, and analysis of the proposed scheme is provided in Section IV. Simulation results are shown in Section V. We conclude the paper in Section VI.

II. Related Work

QoS-based routing protocols were initially developed based on the general restrictions of WSNs. In one of the early attempts, an energy-aware QoS routing protocol for real-time and non-real-time traffic was introduced in [5]. The protocol only considers end-to-end delay and discovers a set of paths for real-time data transmission with specific delay requirements. In SPEED [6], the end-to-end delay is computed by dividing the distance to the sink by the packet speed. However, this approach does not consider any energy metric.

In [7], a Multi-Constrained Multi-Path (MCMP) routing protocol is proposed. MCMP uses certain QoS requirements to deliver packets to the sink. The end-to-end constraint is formulated as an optimization problem and is solved through linear integer programming. However, the protocol tends to forward the packets over nodes that lead to a minimum number of hops, which can result to higher energy consumption in some cases. To extend MCMP, an Energy-Constrained Multi-path (ECMP) routing protocol was introduced in [8]. ECMP formulated QoS routing as an energy optimization problem subject to reliability, play-back delay and geo-spacial path selection constraints. ECMP trades off between the minimum delay and the minimum energy consumption and discovers the path that satisfies the QoS energy constraints. It selects the path with the minimum number of hops and minimum energy. In [9], an Energy-Efficient and QoS-aware routing (EQSR) protocol is proposed. EQSR tries to maximize the network lifetime while using the concept of service differentiation – the traffic is categorized as of high or low importance. An Efficient QoS-aware Geographic Opportunistic Routing (EQGOR) scheme is proposed in [10]. EQGOR is an efficient GOR for multiconstrained QoS provisioning in WSNs. EQGOR selects and prioritizes the forwarding candidate set in a way that is suitable for WSNs in terms of energy efficiency, latency, and time complexity. EQGOR tries to combine the advantages of geographical opportunistic routing along with QoS constraints.

There is also a number of routing schemes specifically designed for WMSNs. A survey on energy-efficient routing techniques with QoS assurances for WMSNs is presented in [11]. In [12] a QoS-aware routing protocol that supports high data rates for WMSNs is discussed. The protocol focuses on end-to-end delay requirements of real-time data. An energy-efficient QoS assurance routing scheme based on cluster hierarchy (EEQAR) is proposed in [13]. EEQAR forms clusters and balances the energy consumption by structure movements.

In this paper, we examine the effect of the forwarding candidate set selection on the network lifetime under delay QoS constraints. The proposed protocol adapts quickly to dynamic changes such as node availability. Moreover, it combines geographical opportunistic routing with optimal forwarding set selection to extend the network lifetime of a WMSN under end-to-end delay restrictions.

III. Network Model

It is assumed that a number of sensor nodes are randomly deployed in a predefined area according to the Poisson distribution. The nodes are static. New nodes can join the network at any time. Nodes can also leave the network because of malfunctions or may not be available permanently or temporarily, in a self-powered scenario, if they run out of energy.

Each sensor node in the network field knows its location with respect to some reference point. Knowledge of the location can be obtained using some localization algorithm. One way to obtain location information is through network broadcasting [14], [15]. The network can have only one source and one destination at any given time. The location of the source can change over time and any node can be the source node of the network. Every node in the network also knows the location of the destination node.

It is assumed that the energy the nodes can use to transmit is limited. Specifically, a given node will no longer be available to help route packets after it has carried out K transmissions, in total. This model applies directly to the case where nodes operate on a battery that needs to be replaced after it is depleted. It also applies to the scenario where a node needs to shut down in order to recharge its batteries (e.g. through energy harvesting [16]) because the recharging rate is smaller than the rate by which the node is used.

The aim of this work is to guarantee transmission with average latency below an upper limit and, at the same time, maximize the lifetime. There are a number of definitions for network lifetime [17]. In this work, the lifetime is defined as the number of packets sent by the source before the routing path is broken because of node failure due to energy depletion.

Clearly, if energy were not an issue, the latency could be minimized by choosing the shortest path between the source and the destination. At the other extreme, the lifetime can be maximized by forming routing paths that involve as many different nodes as possible. However, this may lead to exceeding the latency constraints. We propose optimizing the ADRS that was introduced in [4]. In [4] it was shown that ADRS can be used to provide source location secrecy against an adversary. In this paper we extend the idea and demonstrate how the scheme can also be employed to keep latency under control and improve the lifetime of a WMSN.

IV. Using the Angle-based Dynamic Routing Scheme to improve the network lifetime

In this section, we briefly review the ADRS for completeness. More details can be found in [4]. We then calculate metrics of interest and show how the parameters of ADRS can be chosen to maximize the lifetime of the network.

A. Description of ADRS

In ADRS, a node C that has a packet to transmit seeks forwarding candidate nodes to serve as relays for the next hop that are located inside a specific area. This area is shown in Fig. 1. More specifically, the node T, that will be used for the next hop should be at distance in the range $[r_1, r_2]$ and should not exceed an angle $\pm\frac{\theta}{2}$ around the segment $\mathbf{v}_{CD}$ connecting the current node C, and the destination D.

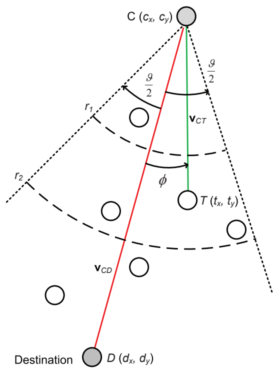


Fig. 1: Selection of a forwarding candidate set for the current node C towards the destination D. A neighbor node T is in the set if it is in distance larger than r_1 and its inclination angle ϕ is smaller than $\pm\frac{\theta}{2}$.

In order to find forwarding candidate nodes, the current node C, floods a Request To Send (RTS) packet to all the neighbor nodes in its transmission range, r_2. The nodes reply using Clear To Send (CTS) packets. Each node sends its CTS packet after time $T_{Backoff}$ [18], which is inversely proportional to the distance between the node and C. The node also transmits its coordinates to C. Hence, C can calculate the distances $\|\mathbf{v}_{CT_i}\|$ and the inclination angle ϕ with respect to $\mathbf{v}_{CD}$, as shown in Fig. 1. If the distance to the neighbor node T_i exceeds a predefined distance r_1 and the inclination angle does not exceed a predefined angle $\frac{\theta}{2}$ then neighbor node T_i is added to the forwarding candidate set. Moreover, the node should be at distance no larger than the transmission range, r_2. In this work, we assume that r_2 is chosen so that the probability of packet error be negligible. It is also assumed that the energy that is required to send CTS packets is negligible compared to the energy required to transmit a DATA packet, and therefore has a negligible impact on the energy of the node [19]. The inclination angle ϕ can be found using the inner (dot) product between two vectors:

$$\langle \mathbf{v}_{CD}, \mathbf{v}_{CT} \rangle = \|\mathbf{v}_{CD}\| \cdot \|\mathbf{v}_{CT}\| \cdot \cos(\phi) \Rightarrow$$
$$\phi = \arccos\left[\frac{\langle \mathbf{v}_{CD}, \mathbf{v}_{CT} \rangle}{\|\mathbf{v}_{CD}\| \cdot \|\mathbf{v}_{CT}\|}\right], \quad (1)$$

where $\mathbf{v}_{CD}$ and $\mathbf{v}_{CT}$ can be calculated easily using the coordinates of points C, D and T.

Let the number of forwarding candidate nodes T_i be N. Each time C needs to route a packet, one of the nodes will be selected randomly to be the next relay node. This is a simple mechanism to increase the lifetime, as sending the packet to the same node every time would lead to depleting its energy and breaking the routing path. The next relay node will follow the same routing principles until the packet reaches the destination.

Note that if a node has zero energy, it will not be included in the forwarding candidate set. The node will not participate in the RTS/CTS handshake, and therefore will not be considered for transmission. The RTS/CTS handshake also helps the network to quickly adapt to any changes in the number of the nodes in the network area caused by nodes entering or leaving the network. This way, there is no need for an initialization phase every time the source node or the network density changes or when the energy of some nodes is depleted.

For fixed r_2, reducing r_1 increases the size of the forwarding candidate set and thus the lifetime, but many candidate nodes will be close to the source node. Hence, the number of hops needed to reach the destination will increase, leading to larger packet latency. Thus, the latency can be regulated using r_1. The latency can also be controlled via the angle θ. Large values of θ lead to more candidate nodes and improved lifetime, but also larger latency. Therefore, there is a tradeoff between the lifetime of the network and the latency. However, there is also a degree of freedom. The lifetime can be improved by either regulating r_1 or θ. In the following we show that, for given latency constraints, large values of θ rather than small values of r_1 should be used.

B. *Mean lifetime*

It is assumed that the nodes follow the 2-dimensional Poisson distribution, and are therefore uniformly distributed on the $x-y$ plane. The number of nodes N, in the forwarding candidate set is a Poisson random variable with parameter λV, where V is the area of Fig. 1, which is equal to

$$V = \frac{\theta}{2}\left(r_2^2 - r_1^2\right). \quad (2)$$

The lifetime of the network is proportional to N, and therefore proportional to V. Consider the first hop from the source to the first relay. If $N = 1$, the same node will always be selected for the first hop, and the routing path will become disconnected after K packets are sent from the source. If $N = 2$, there will be two nodes that can be used for the first hop of the routing path. Therefore, $2K$ packets will be sent before the path becomes disconnected. Hence, for an average number of nodes $\mathbb{E}[N]$, the expected time before the path becomes disconnected at the first hop will be $\mathbb{E}[N] \cdot K = \lambda V K$.

Clearly, the path could become disconnected at a later hop along the routing path. Therefore, $\mathbb{E}[N] \cdot K$ is an upper bound on the lifetime. We argue that when ADRS is used this probability is small and therefore $\mathbb{E}[N] \cdot K$ is a fairly accurate expression for the expected lifetime. As can be seen in Fig. 2, which depicts the first two steps of ADRS, each node C in the forwarding candidate set of the source which, in turn, will select a new forwarding candidate set, "sees" a region with area $V = \frac{\theta}{2}\left(r_2^2 - r_1^2\right)$ equals to the area of the region seen by the source. Hence, each C of the first hop, will "see" the same average number of nodes as the nodes seen by the source S, that is $\mathbb{E}[N]$ nodes on the average. Thus, the number of candidate nodes for the second hop will be larger than $\mathbb{E}[N]$. In the extreme case where the nodes of the first hop are very close to each other and therefore their candidate nodes overlap, there will still be $\mathbb{E}[N]$ candidate nodes for the second hop, on average, and the average lifetime will not drop below $\mathbb{E}[N] \cdot K$. We conclude that the average lifetime equals $\mathbb{E}[N] \cdot K$, and, therefore, is proportional to the area V.

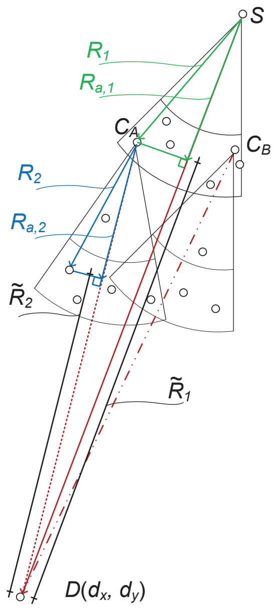


Fig. 2: Calculation of the average number of hops.

C. Mean number of hops

In the following, we provide a brief review of the mean number of hops when ADRS is employed.

We want to calculate the distribution of the distance by which a packet advances towards the destination at each hop i ($R_{a,i}$ in Fig. 2). We first calculate the distribution of the distance R between the current node and the next node. Observing that $R < r$ when no nodes are found in the area between $[r, r_2]$ and $\pm\frac{\theta}{2}$,

$$F_R(r) = \Pr\{R \leq r\} = \frac{\frac{r^2\theta}{2} - \frac{r_1^2\theta}{2}}{\frac{r_2^2\theta}{2} - \frac{r_1^2\theta}{2}} = \frac{r^2 - r_1^2}{r_2^2 - r_1^2},\ r \in [r_1, r_2]. \tag{3}$$

Therefore, the probability density function of R equals

$$f_R(r) = \frac{d}{dr}F_R(r) = \frac{2r}{r_2^2 - r_1^2},\ r \in [r_1, r_2]. \tag{4}$$

Now, let R_a be the projection of R on the segment CD connecting the node to the destination, as shown in Fig. 2. This is the distance by which the packet advances towards the destination along CD during a given hop. Clearly,

$$\begin{aligned} F_{R_a|\Phi}(r_a|\phi) &= \Pr\{R_a \leq r_a|\phi\} \\ &= \Pr\left\{R \leq \frac{r_a}{\cos(\phi)}\right\} = F_R\left(\frac{r_a}{\cos(\phi)}\right) \\ &= \frac{\frac{r_a^2}{\cos^2(\phi)} - r_1^2}{r_2^2 - r_1^2},\ r_a \in [r_1\cos(\phi), r_2\cos(\phi)]. \end{aligned} \tag{5}$$

Hence,

$$f_{R_a|\Phi}(r_a|\phi) = \frac{2r_a}{\cos^2(\phi)(r_2^2 - r_1^2)},\ r_a \in [r_1\cos(\phi), r_2\cos(\phi)]. \tag{6}$$

Given (6) we can calculate the expectation of R_a. After some algebra [4],

$$\mathbb{E}[R_a] = \mathbb{E}_\phi\left[\mathbb{E}[R_a|\phi]\right] = \frac{2(r_2^3 - r_1^3)}{3(r_2^2 - r_1^2)}\frac{\sin(\frac{\theta}{2})}{\frac{\theta}{2}}. \tag{7}$$

Therefore, the average projection of the distance that a packet covers towards the destination on the segment CD of Fig. 2 is given by (7). If the packet is not very close to the destination, we can approximate $\tilde{R}$ in Fig. 2 as $\|CD\| - R_a$. Hence, R_a is approximately equal to the distance by which the packet advances towards the destination. Clearly, the accuracy of this approximation worsens as the packet nears the destination, and $\tilde{R} > \|CD\| - R_a$. However, it will be good for the majority of the hops towards the destination.

If the distance between the source and the destination is equal to $\|SD\|$, the average number of hops can be approximated by

$$\bar{H} = \frac{\|SD\|}{\mathbb{E}[R_a]}. \tag{8}$$

Even if the value of $\mathbb{E}[R_a]$ were exact, the average (8) would not be perfectly accurate, since in the last hop when the last intermediate node locates the destination it will send the packet deterministically to the destination. However, as was shown in [4], (8) leads to an estimate of the average number of hops that, although slightly optimistic, is fairly accurate.

D. Selection of the parameters of ADRS for maximum lifetime

From (7) and (8),

$$\begin{aligned} \bar{H} &= \frac{3\|SD\|}{2}\frac{r_2^2 - r_1^2}{r_2^3 - r_1^3}\frac{\frac{\theta}{2}}{\sin(\frac{\theta}{2})} \\ &\overset{(2)}{=} \frac{3\|SD\|}{2(r_2^3 - r_1^3)\sin(\frac{\theta}{2})}V. \end{aligned} \tag{9}$$

Guaranteeing transmission below a certain limit on the number of hops, and, therefore, the latency places a constraint on θ and r_1, and indirectly on V and the resulting lifetime. However, we have the freedom to regulate $\bar{H}$ through either r_1 or θ. For the network densities and distances considered in this paper, it turns out that using large values for θ instead of small values for r_1 leads to larger average lifetime for a given value of $\bar{H}$. Therefore, we propose the following strategy. For given $\bar{H}$ set θ to its maximum allowed value (not exceeding $\frac{\pi}{2}$ for a square area). Then find the value of r_1 that satisfies (9). When using ADRS this will lead to the largest possible average lifetime, as it maximizes the value of V for given $\bar{H}$.

As a side remark, note that larger values of V improve the secrecy of the protocol, as the number of nodes that are used for routing increases.

V. Simulation Results and Performance Evaluation

To evaluate the performance of the protocol, OMNeT++, a discrete event simulator was used. ADRS is compared with the simple shortest-path routing scheme in terms of number of hops, latency, transmitting nodes and lifetime. The selection of the shortest path routing scheme for comparison is in order to verify that the network lifetime is extended, whereas packet latency remains close the best possible.

In the shortest-path approach, there is only one path between the source and the destination that is used for every packet transmission. Every node forwards all the packets towards the same neighbor node. This neighbor node is the node closer to the destination, i.e. provides the fastest packet advancement.

A. Simulation Setting

The sensor nodes are placed in a $100 \times 100\ m^2$ square area. They follow the Poisson distribution with $\lambda = 0.16$. The transmission range of each node is $r_2 = 12\ m$. Eight different topologies were evaluated. The number of the nodes varied between 1526 and 1650 and the distance between the source and the destination was between 130 and 138 meters. For every topology 1000 packets were generated from the source towards the destination.

For ADRS we consider six different combinations of angles and range r_1, as shown in Table I. The parameters are chosen so the average number of hops be equal to 15, following (9).

B. Evaluation Metrics

Four metrics were selected to evaluate the effectiveness of the scheme:

- *Packet latency*: The time a packet requires to reach the destination.
- *Hop count*: The average number of hops towards the destination.
- *Transmitting node distribution*: The location of the nodes that participate in a DATA packet transmission.
- *Lifetime*: As was mentioned in Section III, in this work, the lifetime is the number of packets successfully transmitted by the source before the lost of connectivity between the source and the destination.

C. Performance Analysis

The ADRS and the shortest-path protocols were evaluated over the same eight topologies.

The average packet latency of the different approaches is shown in Fig. 3. The packet latency for the ADRS approach is slightly higher than that of the shortest-path scheme. It is important to notice that the latency remains similar under the different configurations and the different topologies, as predicted by the analysis, since the density of the network and the average distance between the source and the destination are the same for all topologies.

Parameter set	Angle θ (degrees)	Range r_1 (meters)
1	15	5.71
2	30	5.93
3	45	6.28
4	60	6.79
5	75	7.42
6	90	8.2

TABLE I: Parameter sets used for the simulations.

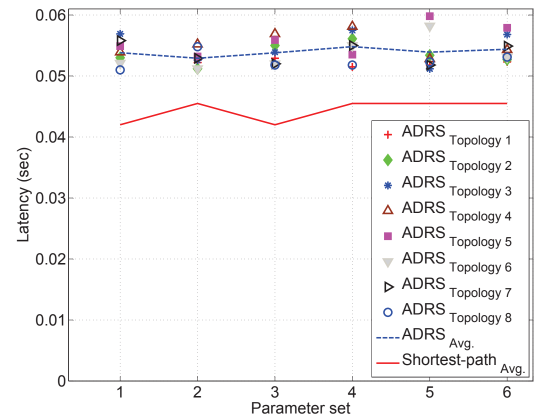


Fig. 3: Average packet latency for the parameter sets of Table I.

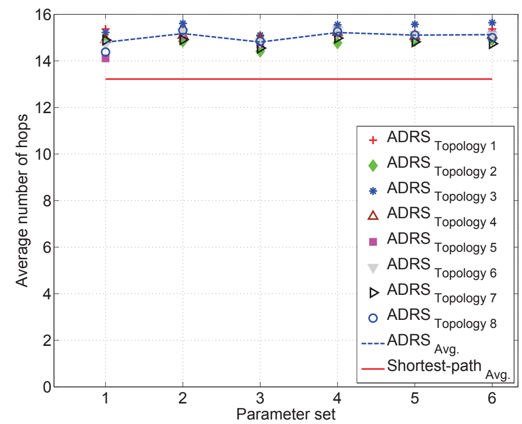
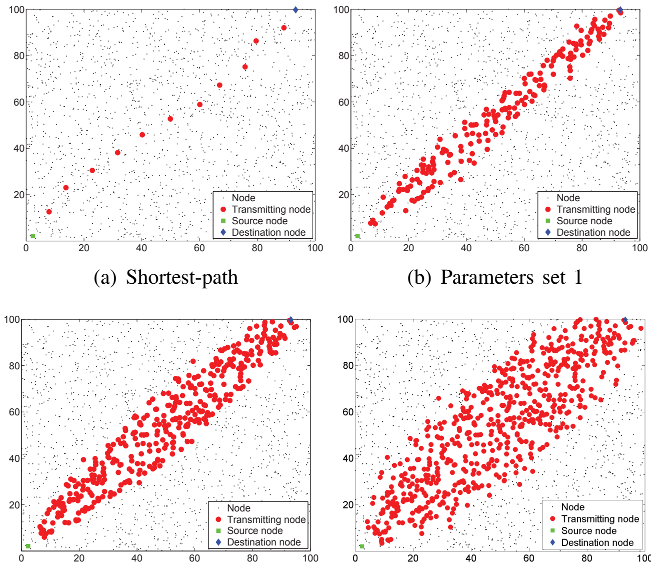


Fig. 4: Average number of hops for the parameter sets of Table I.

Figure 4 shows the performance of the protocols in terms of average hops from the source towards the destination. Shortest-path routing does not consider the angle; hence it has an average latency of 13.2 hops. The proposed ADRS scheme has slightly higher latency, approximately two additional hops. Although the angle-range set changes, the average number of hops remains similar. This is because the parameters are chosen so that (9) remain constant. As the angle increases, the range increases as well. However, the packets reach the destination at almost the same time.

Figure 5 shows the transmitting node distribution of one of the topologies - Topology 6. Shortest-path routing uses the same nodes for every packet transmission, hence there is only one path between the source and the destination. On the other hand, ADRS can discover more paths for a small penalty on the delay. Moreover, it is clear that, as we increase the inclination angle, the number of the nodes that participate in packet transmission increases, although the delay remains the same because r_1 is increased.

Figure 6 shows the performance of the protocols in terms of lifetime. For simulation purposes we assume that a node runs out of energy after $K = 30$ packet transmissions. As expected, shortest-path routing has a lifetime of 30 packets because it uses the same nodes for all the packet transmissions. When the energy level of a node is not sufficient for packet transmission



(a) Shortest-path (b) Parameters set 1

(c) Parameters set 3 (d) Parameters set 6

Fig. 5: Energy distribution for the different approaches.

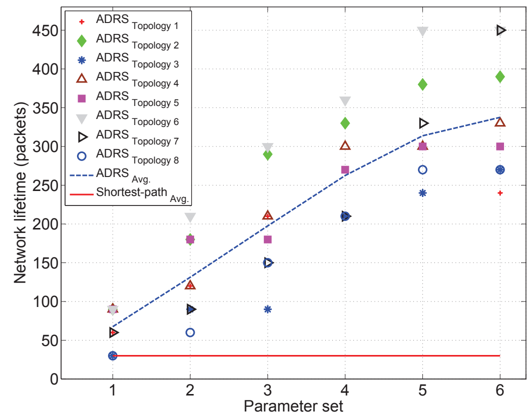


Fig. 6: Lifetime of the different approaches.

the network connectivity is lost.

On the other hand, ADRS performs significantly better than shortest-path routing in terms of network lifetime. As the angle increases the lifetime increases as well and ADRS outperforms shortest-path routing.

Returning to the two issues mentioned in Section I, forwarding candidate set selection has great influence on the network lifetime. As can be inferred, ADRS can extend the network lifetime in a WMSN for a small increase of the latency. Moreover, ADRS becomes more efficient as the angle and the range increase.

VI. Conclusions

In this paper it was shown that the lifetime of a WMSN can be improved by using the ADRS method, which creates multiple paths to route packets from the source to the destination. The multiple paths are created by using relaying nodes that are within an inclination angle and within a certain range around the direction from the current node to the destination. In adequately dense networks, the increase in lifetime can be substantial compared to the standard, shortest-hop routing scheme, and only requires a small increase in the latency. Moreover, the scheme is dynamic and of low complexity, and can therefore adapt easily and rapidly to changes in topology, including changes because of nodes going offline due to inadequate power or recharging.

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