Detours Save Energy in Mobile Wireless Networks

Chia Ching Ooi and Christian Schindelhauer

Chia Ching Ooi · Christian Schindelhauer
Albert-Ludwigs-Universität Freiburg, Computer Networks and Telematics, Georges-Köhler-Allee 51, 79110 Freiburg, Germany, e-mail: {ooi, schindel}@informatik.uni-freiburg.de

Abstract Autonomous robotic systems have been gaining the attention of research community in mobile ad hoc network since the past few years. While motion cost and communications cost constitute the primary energy consumers, each of them is investigated independently. By taking into account the power consumption of both entities, the overall energy efficiency of a system can be further improved. In this paper, the energy optimization problem of radio communication and motion is examined. We consider a hybrid wireless network that consists of a single autonomous mobile node and multiple relay nodes. The mobile node interacts with the relays within its vicinity by continuously communicating high-bandwidth data, e.g. triggered by a multimedia application like video surveillance. The goal is to find the best path such that the energy consumption for both mobility and communications is minimized. We introduce the Radio-Energy-Aware (*REA*) path computation strategy by utilizing node mobility. Given the starting point, the target point and the position of the relays, our simulation results show that the proposed strategy improves the energy efficiency of mobile node compared to the Motion-Energy-Aware (*MEA*) path constructed based only on the mobility cost.

1 Introduction

With the unprecedented growth of wireless communication technologies witnessed over the past two decades, intensive researches [1] have been conducted to improve the performance of communications in mobile wireless network. Among them, a number of improvements were achieved [2, 3] through the extensive investigation of node mobility. However, most of the existing literature assumes that mobility cannot be controlled. A mobile node in a wireless network can be a mobile handheld device, a manned or unmanned vehicle, a mobile robot, or a combination of them. Among them, the artificial mobile nodes are capable of controlling their own movement but the natural mobile nodes are not.

Recently, networked robotics has been gaining increasing interest among robotic and mobile networking research community. Many modern mobile robots are already equipped with networking capabilities [4, 5], using either radio frequency, or infra-red communications. Multi-robot systems (MRS) [6, 7, 8, 9] take the advantage of collective and cooperative behavior of robot team through inter-robot communications. Swarm robotics [10, 11] is an example of MRS that deploys and coordinates large number of relatively simple physical robots to complete the assigned tasks as a team.

The co-location of the motion and task control systems with the communications mechanisms in a robot enables the co-exploitation of individual subsystems, providing a completely new kind of networked autonomy. However, only little on-going researches make use of this advantage. Our paper explores this uniqueness of an artificial mobile node to achieve energy optimization.

The remainder of the paper is organized as follows. Section 2 reviews related work. In Section 3, we present the system and the energy models used in our research and define the problem of computing the minimal-energy detour for a mobile robot. Based on these foundations, we propose an optimal-energy path computation strategy and analyze the algorithm in Section 4. The proposed scheme is evaluated through simulation described in Section 5. Lastly, we make concluding remarks and discuss future works.

2 Related Work

A mobility control scheme is proposed in [12] to improve the communication performance. They show that controlled mobility increases network performance through extensive evaluations on its feasibility. However, this scheme mandates all relay nodes to move to the optimal configurations in order to optimize the communications performance. Therefore, it can not be applied to certain applications that consist of static node or node restricted to move.

The authors of [13] have similar objectives and another approach. They focus on optimizing the positions of relay nodes for a single source-destination pair. Both works involve high number of relays, and consequently, high power efficiency can be achieved in the entire network. We propose a different approach by making use of node mobility of the source to optimize its energy consumption, given that the relay node is restricted from moving, for instance, due to the assigned task.

In [14], Liu et al. proposed a resource-aware movement strategy to achieve energy conservation by guiding the nodes movement and utilizing node heterogeneity. However, motion cost for mechanical movement is not taken into consideration as they assume all communication devices are carried by people moving on foot.

Our work is motivated by the natural fact that radio energy degrades over the transmission range, and the limited energy resource carried by most mobile nodes. A study of mobile ad hoc networks based on *Khehera* [21] provide the practical insights that in certain environments, motion cost and communications cost constitute the primary energy consumers. While the mobility cost increases linearly, the communication cost grows at least quadratically with the communication distance. Thus, it is advantageous to move a robot towards its communicating node at a certain radio range.

Recently, the optimization problem of motion and communication cost was studied in [15]. Taking a single-robot single-base station scenario, they solved the problem by using a proposed approximation algorithm based on Dijkstra's algorithm to compute the minimal energy path, and show that up to nearly 50% of total energy can be saved. However, it can be achieved only if the robot is allowed to move more than half of the transmission distance relative to its originally planned path, which is not applicable to many scenarios.

In this paper, we study how a minimal-energy detour can be computed to optimize the energy consumption of a mobile robot in a multiple relay wireless network. Motivated by the emergence of the promising wireless technology like IEEE 802.11n [16] and wireless multimedia sensor network [17], we are interested in the applications in which a team of mobile robots has to exchange a high volume of data over the wireless medium among themselves, or to its base station through multiple relays. We concentrate on optimizing the energy consumed by both mobility and communications.

3 Preliminaries

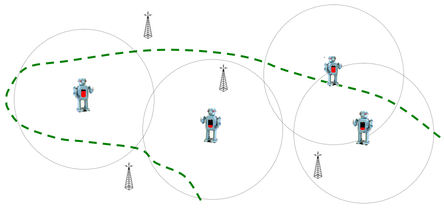
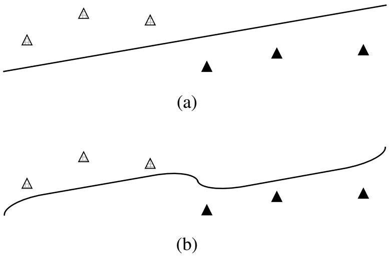


Fig. 1 Mobile Robots and Relay Stations



(a)

(b)

Fig. 2 Energy-Aware Paths **(a)** A *MEA* Path **(b)** A *REA* Path

As shown in Fig. 1, we consider a hybrid wireless network that consists of a team of autonomous mobile robots and multiple relays. All nodes can communicate with each other wirelessly. The lifetime of a robot is limited to the energy resource it carries along. Every robot is assigned with different task(s): searching, exploring, sensing, foraging, and so on. Some are required to transmit the mission-specific data directly or via relay(s) to a target node. The relay can be either a static node such as a base station or an access point, or a mobile node. An example scenario is that a robot is deployed to collect data from sensors [18] and transmit them to the target via single- or multi-hop communications, forming a robot-assisted wireless sensor network. Another potential application is the robot surveillance system [19].

We assume that every point on the robot navigation area is covered by at least one relay. The positions of the relays are known prior to path computation. The robot knows the Euclidean distance to the relay within its vicinity, which serves as the destination of the data transmission.

On the other hand, at any instant, a mobile robot is assumed to know its route towards its next destination, which is planned based only on the motion cost and equal to the Euclidean distance between a robot's start point and target point. We call this route a motion-energy-aware (*MEA*) path. A *MEA* path is a straight line because moving on Euclidean distance costs minimal motion energy. *MEA* path is not necessarily the optimal energy path since the robot consumes the energy not only for the movement but also for the wireless communications. A minimal energy path constructed based on both the communication and motion cost is called a Radio-Energy-Aware (*REA*) path in the rest of the paper. Fig. 2 shows the examples of both *MEA* and *REA* paths.

3.1 System Model

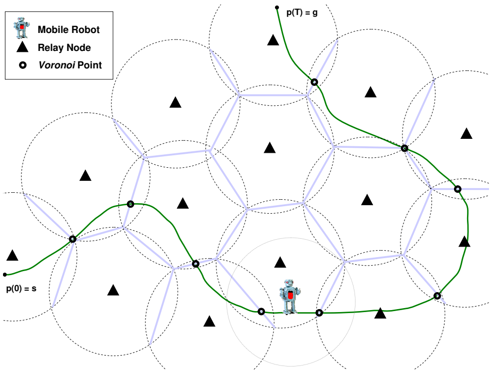


Fig. 3 Navigation Area of Mobile Robot in a Multi-relay Network

The navigation area of a mobile robot is modeled on a two dimensional Euclidean space as illustrated in Fig. 3. The node position is indicated as a continuous function of time $p : [0,T] \mapsto \mathbb{R} \times \mathbb{R}$ such that the position of the mobile robot at time t in Cartesian Coordinates is $p(t) = (p_x(t), p_y(t))$. At the beginning, we have $p(0) = s$ where s denotes the start position of the node. At the end, we have $p(T) = g$, where g is the target position. Both positions are obtained from *MEA* path. When we compute the path, we approximate the path by k sub-paths of constant speed $P = ((t_0, x_0, y_0), (t_1, x_1, y_1), \ldots, (t_k, x_k, y_k))$ for $t_0 < t_1 < \cdots < t_k$ where the corresponding path function is given by

$$p(t) = \left(x_i + \frac{(t - t_i)(x_{i+1} - x_i)}{t_{i+1} - t_i}, y_i + \frac{(t - t_i)(y_{i+1} - y_i)}{t_{i+1} - t_i} \right) ,$$

for $t \in [t_i, t_{i+1})$.

A set of static relays is defined as $R = \{r_1, ..., r_m\}$, where m represents the number of relays interacting with mobile robot moving on path P, and $r_i = (r_{i,x}, r_{i,y})$. Let the maximum radio range of all nodes be R_{max} and the relay in use at t be r_i. The transmission range between robot and relay for all $t \in [0,T] : ||p(t) - r_i||_2 \leq R_{max}$, where $||u-v||_2 = \sqrt{(u_x - v_x)^2 + (u_y - v_y)^2}$. Due to the limited radio range, the robot needs to switch to different relay whenever it moves out of the vicinity of current relay. The switching of relay happens at a set of positions on *MEA* path, indicated by a set of *Voronoi* points, $V = \{v_1, ..., v_{m+1}\}$, where $v_1 = s$ and $v_{m+1} = g$.

Every consecutive *Voronoi* point pair, v_i and v_{i+1}, defines a path segment, s_i, and a relay, r_i. Robot moving on s_i communicates only with r_i, which transmission range, $R_i = ||p(t) - r_i||_2 \leq ||p(t) - r_j||_2$ for $j \neq i$ and $1 \leq j \leq m$. Therefore, this link has the lowest transmission cost given that the radio condition of the transmission medium between robot and all relays in range are the same. While the robot communicates with relay r_i, all other relays of set R are free for communications with other nodes.

A *MEA* path, P_{mea} is composed of multiple fragments f and defined as $P_{mea} = \{f_1, \ldots, f_k\}$, where k is the number of fragments. Meanwhile, a fragment consists of multiple segment s, and is defined as $f_j = \{s_{j,1}, \ldots, s_{j,q_j}\}$, where the total number of segments on P_{mea} is given by $m = \sum_{i=1}^{k} q_j$. We explain how to determine a fragment from a *MEA* path in Section 4.

3.2 Energy Models for Robot

As the robot communicates with relays while moving, its energy model comprises mobility cost and communication cost. For robot motion, we adopt the energy model $E_m = m \cdot d_m$, where d_m is the distance traversed by the robot in *meter* and the movement parameter, m, in *Joule/meter*, is a constant value determined by the mass of the robot, the friction to the surface, gravity and acceleration. This model is suitable for wheeled robot [12], and is adopted by [13, 15, 20].

We refer to [13, 15, 22] for the communications energy models. The transmit energy model $E_{tx}(\ell, d_c) = \ell \cdot (d_c^{\alpha} \cdot e_{tx} + e_{cct})$ is used for transmission of ℓ bits data over d_c measured in *meter*, where e_{tx} is the energy consumed by the power amplifier of transceiver to transmit one bit data over one meter, and e_{cct} is the energy used by the transceiver to transmit or receive one bit, measured in *Joule/bit*. Depending on the condition of wireless transmission medium, α ranges from 2 to 6. On the other hand, the energy consumption for receiving ℓ bits data is defined as $E_{rc}(\ell) = \ell \cdot e_{cct}$, which is independent of the distance between communicating nodes.

3.3 Multi-Relay Communications Model

We modify the Position-critical Communications Model (PCM) of [15] designed for single relay communication. A sequence of tasks $Q_1, \ldots, Q_n$ is defined for the mobile robot. Each task $Q_i = (A_i, B_i)$ consists of a region A_i from which the robot may choose a point $p_i \in A_i$ and the size of data B_i the robot needs to transmit. A robot path solves the task $Q = ((A_1,B_1),\ldots,(A_n,B_n))$ at points $(x_1,\ldots,x_n)$ if $\exists t_1 < t_2 < t_3 < \cdots < t_n$ with $p(t_i) = x_i$ and $x_i \in A_i$.

Based on the energy models described in Section 3.2, the energy consumption of a robot with path p and solution points $x = (x_1,\ldots,x_n)$ is then defined as:

$$E_{pcm}(Q,p,x) := E_{tx}(Q,p,x) + E_m(p) ,$$

where $E_{tx}(Q,p,x) = \sum_{i=1}^{n} B_i \cdot (||x_i - r_c||_2)^{\alpha} \cdot e_{tx}$, $E_m(p) = m \cdot D$, and D is the path length of p. In $E_{tx}(Q,p,x)$, r_c is the current relay node interacting with robot at x_i. In a multi-relay network, we are interested in the accumulated energy consumption of the mobile robot moving from s to g, denoted as $E_{total}(p)$. Using the system model defined in Section 3.1, we have:

$$E_{total}(p) = \sum_{j=1}^{k} E_{pcm,j}(Q,p,x) ,$$

where $E_{pcm,j}(Q,p,x) = \sum_{w=1}^{q_j} \sum_{i=1}^{n} (B_{i,w} \cdot (||x_{i,w} - r_c||_2)^{\alpha} \cdot e_{tx} + m \cdot D)$.

3.4 Minimal-Energy Detour Problem Statement

The minimal-energy detour is also called the *REA* path. In this problem, the location of relay nodes, the initial and target position of the mobile robot are given. The mobile robot communicates with multiple relays while moving towards its target position. The goal is to find the optimal energy path to reach the given target point.

Definition. *The path optimization problem for multi-relay communications model. Given a sequence of tasks* $Q = ((s,0),(A_1,B_1),\ldots,(A_w,B_w),(g,0))$ *and a set of relay, R, the mobile robot has to find a (discrete) path* $(s,x_1,\ldots,x_w,g)$ *that solves the tasks, i.e.* $x_i \in A_i$ *for all* $i \in \{1,\ldots,w\}$, *and minimizes the total energy* $E_{total}(p) = \sum_{j=1}^{k} E_{pcm,j}(Q,p,x)$.

4 Algorithms

We introduce *REA* path computation strategy described in Fig. 4. The resulting *REA* path, P_{rea}, has minimum total cost of motion and communication for mobile robot.

Fig. 6 shows the breakdown of a *MEA* path into fragments and segments defined in Section 3.1. Let ρ_{r_i} be the polarity of the relay r_i. To determine which fragment a segment s_i belongs to, ρ_{r_i} must be first determined based on the position of r_i relative to *MEA* path as follows: Taking $p(0) = (0,0)$, $\rho_{r_i} = 1$ for $r_{i,y} > p_y(t)$ at $r_{i,x}$, $\rho_{r_i} = 0$ for $r_{i,y} = p_y(t)$ at $r_{i,x}$, and $\rho_{r_i} = -1$ for $r_{i,y} < p_y(t)$ at $r_{i,x}$. Successive relays

```
**Radio-Energy-Aware Path Computation**
    Obtain *MEA Path*, $P_{mea}$
    Identify *Voronoi* point set, $V$
    Obtain relay node set, $R$ and its polarity, $\rho_R$
    $i, j \leftarrow 1$
    $f_j.sp \leftarrow v_i$
    while $i \leq m$
        if $\rho_{r_i} \neq \rho_{r_{i+1}}$
            $f_j.ep \leftarrow v_{i+1}$
            $f_{j+1}.sp \leftarrow v_{i+1}$
            if $\rho_{r_i} = 0$
                $f_j \leftarrow \{s_{f_j.sp}, \ldots, s_i\}$
            else
                Run modified PCM-Dijkstra-
                    Refinement algorithm
                $f'_j \leftarrow p_{\varepsilon'}$
            end of if
        Increment $j$
        end of if
        Increment $i$
    end of while
return *REA Path*, $P_{rea} \leftarrow \{f'_1, \ldots, f'_k\}$
```

Fig. 4 *REA* Path Computation

```
**Modified PCM-Dijkstra-Refinement**
    Obtain relay node set, $R$
    Obtain $f_j.sp$ and $f_j.ep$
    $s \leftarrow f_j.sp$
    $g \leftarrow f_j.ep$
    Carefully choose parameters $c, k > 1$
    $\varepsilon' \leftarrow \frac{||s,g||_2}{c}$
    Construct $G_{\varepsilon'}$
    Use Dijkstra's algorithm to compute
        optimal path $p_{\varepsilon'}$ in $G_{\varepsilon'}$
    while $\varepsilon' > \varepsilon$
        $\varepsilon' \leftarrow \varepsilon'/c$
        Refine around $p_{\varepsilon'}$:
            Construct graph $G_{\varepsilon'}$
            Erase all nodes in $V_{\varepsilon'}$ which are not
                within $k \cdot \varepsilon'$ distance to a node of $p$
            Erase all edges adjacent to erased
                nodes
        Use Dijkstra's algorithm to compute
            optimal path $p_{\varepsilon'}$ in resulting graph $G_{\varepsilon'}$
    end of while
return $p_{\varepsilon'}$
```

Fig. 5 Modified PCM-Dijkstra Algorithm

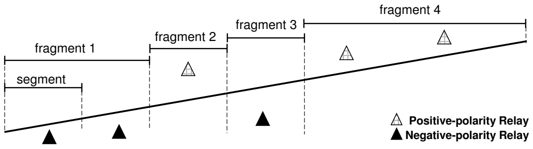


Fig. 6 Fragment, Segment and Polarity of Relay Node relative to *MEA* Path

having the same ρ_{r_i} are grouped into the same fragment. Given the set of relay R, once ρ_{r_i} for all relays are determined, the *REA* path computation strategy constructs a set of fragment F of a given *MEA* path, P_{mea}. For each fragment f_j, a modified PCM-Dijkstra-Refinement algorithm explained next is used to compute a minimal-energy detour, f'_j. The final output of the strategy is an optimal-energy *REA* path, $P_{rea} = \{f'_1, \ldots, f'_k\}$.

The PCM-Dijkstra-Refinement algorithm [15] was designed to cope only with one-robot one-relay scenario. As showned in Fig. 5, we modified it to solve the optimal energy path problem in multiple relay communications. The algorithm is invoked for each fragment that composes the *MEA* path, with fragment f_j as an input and the optimal-energy fragment, f'_j as the output. A fragment f_j may contain multiple segments, and thus, multiple relays. Therefore, before running the algorithm, we need to determine fragment start point, $f_j.sp$, fragment end point, $f_j.ep$, and set of relays, R.

According to the PCM-Dijkstra-Refinement algorithm in [15], a finite candidate set $V_{i,\varepsilon} = y_{i,1}, y_{i,2}, \ldots \in A_i$ has to be selected such that for all $u \in A_i$ within the transmission range of a relay node, a candidate $y_{i,j}$ exists within distance ε. This is done by using a two-dimensional grid positions with distances of at most

$\frac{\varepsilon}{\sqrt{2}}$. This candidate can be placed with distance ε if the task areas are lines. To construct a graph $G_\varepsilon = (V_\varepsilon, E_\varepsilon)$, the node set $V_\varepsilon = \bigcup_{i \in \{1,\ldots,n\}} V_{i,\varepsilon}$ and the edge set $E_\varepsilon = \bigcup_{i \in \{1,\ldots,n-1\}} V_{i,\varepsilon} \times V_{i+1,\varepsilon}$ are defined. The weight function for the edges is defined as below:

$$w(y_{i,j}, y_{i+1,k}) = B_i \cdot (||y_{i,j} - r_c||_2)^\alpha \cdot e_{tx} + m \cdot ||y_{i,j}, y_{i+1,k}||_2$$

for $i < n-1$ and all j,k. For $i = n-1$, we define the weight function, $w(y_{n-1,j}, y_{n,k}) = (B_{n-1} \cdot (||y_{n-1,j} - r_c||_2)^\alpha + B_n \cdot (||y_{n,j} - r_c||_2)^\alpha) \cdot e_{tx} + m \cdot ||y_{n-1,j}, y_{n,k}||_2$. Note that the weight of $w(p)$ represents the energy consumption of a mobile robot on this path. Now, let $p_{\min}$ be the minimal-energy path in the original problem. By the definition of G_ε, a path p exists in G_ε such that $||p_{\min,i} - p_i||_2 \leq \varepsilon$. Thus,

$$|E_m(p_{\min}) - E_m(p)| \leq m \cdot \varepsilon \cdot (n-1) \ .$$

It indicates that $|E_{tx}(p_{\min}) - E_{tx}(p)| \leq e_{tx} \cdot \varepsilon \cdot \alpha \cdot (R_{\max} + \varepsilon)^{\alpha-1} \cdot \sum_{i=1}^{n} B_i$, where $R_{\max}$ is the maximum transmission distance of the relay node. Therefore, the theorem below follows:

Theorem 1. *With respect to the weight function w, the minimal weighted path in* G_ε *approximates the minimum energy by an additive term of* $m \cdot \varepsilon \cdot (n-1) + e_{tx} \cdot \varepsilon \cdot \alpha \cdot (R_{\max} + \varepsilon)^{\alpha-1} \cdot \sum_{i=1}^{n} B_i$.

Therefore, we can use Dijkstra's shortest path algorithm to solve the approximation of the minimum energy path problem. However, if the task areas A_i are regions, i.e. containing some small-sized disk, the number of nodes of G_ε grows proportional to $\Theta(\frac{1}{\varepsilon^2})$ and the size of the edge set grows by $\Theta(\frac{1}{\varepsilon^4})$, which is the decisive term of Dijkstra's algorithm.

Introducing the heuristic refinement strategy shown in Fig. 5, we can improve its running time considerately. The following theorem shows that this algorithm is very efficient.

Theorem 2. *The PCM-Dijkstra-Refinement algorithm has an asymptotic running time of* $\mathcal{O}(n \cdot \log(\frac{1}{\varepsilon}))$ *for general task areas aiming at an additive error bound of* $\mathcal{O}(\varepsilon)$.

5 Performance Evaluation

In this section, we study the impact of various parameters on the performance of the proposed scheme and compare it with that without using our approach. Two main criteria of our evaluation are the percentage and the total energy saving that can be achieved by the mobile robot using the proposed scheme. The first criterion shows the performance gain of *REA* path, while the latter is important to determine if *REA* path computation is beneficial for different scenarios.

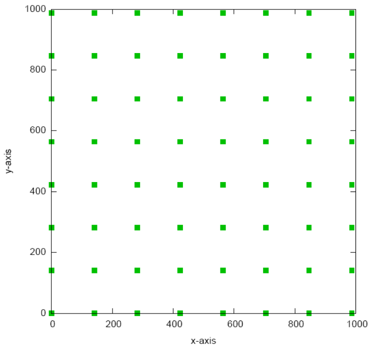


Fig. 7 Location of Relays in Simulation

Simulation Environment Parameter	**Value**
Field size, (m^2)	1000 × 1000
Number of relay node	64
Maximum transmission range, R_{max} (m)	100

Parameter	**Value(s)**
Energy consumed by transceiver circuitry to transmit or receive a bit, e_{cct} (Joule)	10^{-7}
Energy consumed by transceiver amplifier to transmit one bit data over one meter, e_{tx} (Joule)	10^{-12}
Energy to receive a bit, e_{rc} (Joule)	10^{-7}
Path loss exponent, α	3, 4
Data size, B (MB)	1, 2, 3
Maximum detour gap allowed, G (m)	1 to 10
Energy to move robot over one meter, m (Joule)	1, 2

Fig. 8 Simulation Parameters

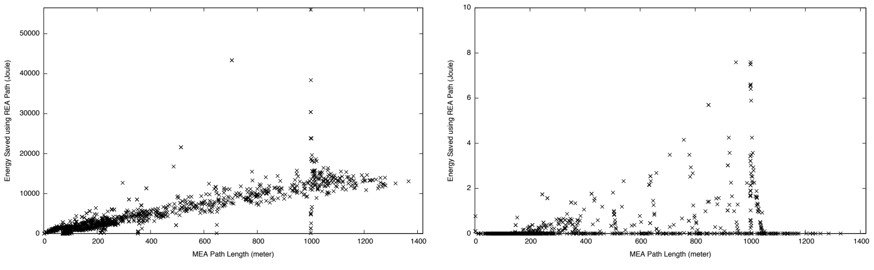
5.1 Simulation Environment Setup

We simulate 64 static relays on an area of 1000m×1000m as illustrated in Fig. 7. This simplified simulation model is sufficient to provide various situations that require a robot to interact with multiple relays while traveling towards a target. The robot needs to switch to the best relay at a number of *Voronoi* points as explained in section 3.1.

At the beginning, a *MEA* path is constructed by randomly selecting a start point on the left edge and an end point on the right edge of the simulated area. A mobile robot is deployed to travel from the start point to the end point while transmitting mission-specific data to selected relays. The maximum transmission range of all nodes are assumed to be 100m, which is applicable to most 802.11 standards [23]. Simulation results shown in [15] indicate that higher maximum radio range yields more energy saving. The transmission range between robot and relay changes based on the instantaneous robot position on the path, relative to the location of the relay in use.

Fig. 8 shows the simulation parameters. e_{cct}, e_{tx}, e_{rc}, are assigned according to [22]. A robot may perform its assigned tasks in indoor or outdoor environment. To simulate different environments, the path loss exponent α is varied from 3 to 4. We eliminate $\alpha = 2$ because it is hardly achieved in realistic environment. The data size used, B, ranges from 1 to 3 MB, and is suitable for multimedia data transmission for the applications stated in Section 1. We simulate the robot to transmit B data at each meter of *MEA* path within its task region.

Moreover, depending on the application, robot movement is restricted within a task-specific area between the relay and a *MEA* path. We introduce the parameter G to indicate the maximum gap allowed between *REA* and *MEA* path. It also serves as the tuning parameter for applications with specific delay tolerance if a robot moves on a longer path, as a balance of energy and delay trade-off needs to be achieved. Lastly, we vary the motion power constant m between 1 and 2*J/m*. These values are applicable to wheeled robots weighed between 10 to 20kg travelling on a flat



(a) (b)

Fig. 9 Overall Energy Saving Achieved using *REA* Path **(a)** Maximum energy saved (α=4, B=3, G=10, m=1) **(b)** Minimum energy saved (α=3, B=1, G=1, m=2)

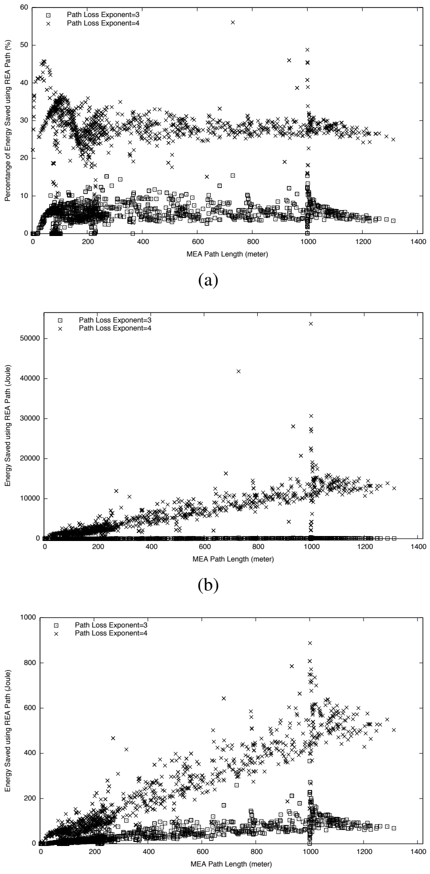
surface [15], for instance, *Khepera II* at 80g to 250g, and *Khepera III* at 690g to 2kg [4], *s-bot* at 660g [11], and *e-puck* at 150g [5]. Robots at lighter weight (lower *m*) further improve the performance of *REA* path. By using various combination of these parameters, we perform 100 simulation runs for each combination and compute the total and percentage of energy saved by the robot.

5.2 Simulation Results

In every simulation run, total energy saved is recorded at the end point of each fragment, $f_{i\cdot e}p$ and the target position, g. Different *MEA* path length can be simulated up to the maximum length of $\sqrt{2\cdot 1000^2}$, based on the size of the simulated area.

Fig. 9 shows the two simulations producing the maximum and minimum energy saved. In both cases, the highest energy saving is observed when a straight path appears at a certain distance in parallel to a row of relays. In Fig. 9(a), α, B, G are set to the maximum values, while m at its minimum. On the contrary, in Fig. 9(b), α, B, G are at the minimum values, while m at its maximum. We will describe how α, B, G contribute to the performance gain of the proposed strategy. Moreover, in order to determine if the *REA* path computation is worth running, it is important to note the overall minimum energy saved in our simulation. More about it will be elaborated at the end of the section.

Impact of Path Loss Exponent, α. Fig. 10 illustrates the effect of varying α on the energy saving by using different *MEA* path lengths. First, in Fig. 10(a), by fixing the parameters B=3, G=10, m=1, the *REA* paths save around 30% and 7% on average for α=4 and α=3 respectively. We will observe later that the impact of α is comparably high among all parameters. Next, to illustrate the total energy saved, we choose the combination of parameters that produces two best results when α=3 and α=4. Using B=3, G=10, m=1, the impact of α is illustrated in Fig. 10(b). It shows the very large difference of energy saving with various α. We further analyze the impact of α by selecting the combination of parameters (B=1, G=1, m=2) that produces the minimum energy saving for α=4, and comparing it with that of α=3

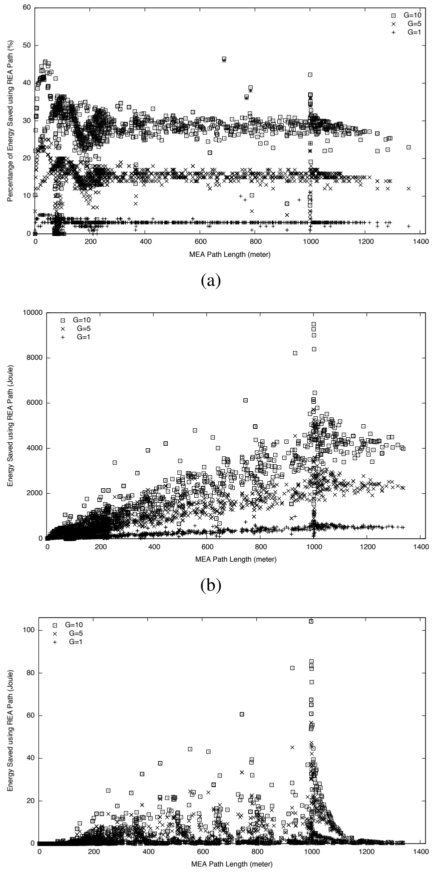


(a)

(b)

(c)

Fig. 10 Varying Path Loss Exponent **(a)** Percentage of Energy Saving (B=3, G=10, m=1, α=4 vs. α=3) **(b)** Maximum Energy Saving Difference (B=3, G=10, m=1, α=4 vs. α=3) **(c)** Minimum Energy Saving Difference (α=4, B=1, G=1, m=2 vs. α=3, B=3, G=10, m=1)



(a)

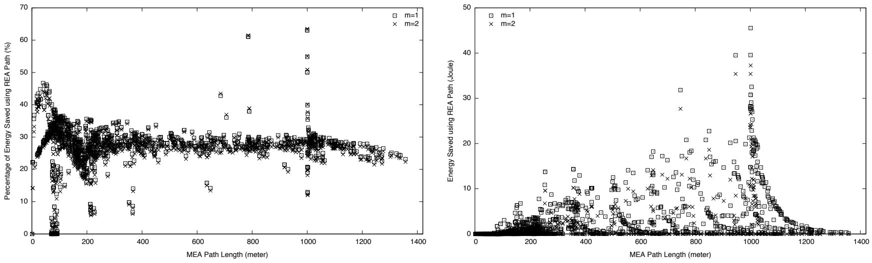
(b)

(c)

Fig. 11 Varying Maximum Detour Gap Allowed **(a)** Percentage of Energy Saving for G_1, G_5, G_{10} (α=4, B=3, m=1) **(b)** Energy Saving Difference for G_1, G_5, G_{10} (α=4, B=1, m=1) **(c)** Energy Saving Difference for G_1, G_5, G_{10} (α=3, B=1, m=1)

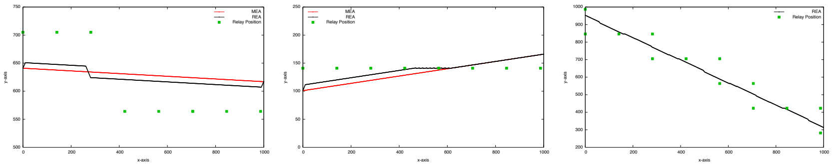
in the first case. As shown in Fig. 10(c), the energy saving difference is lower, but still high compared to the influence of other parameters to be described next.

Impact of Maximum Detour Gap Allowed, *G*. Fig. 11 shows the impact of varying G on the performance of *REA*. As explained in Section 5.1, a task region A_i is application-dependent. To simulate various sizes of A_i, we introduce a set of $G = \{G_1, G_2, \ldots, G_{10}\}$, where $G_i = i$. First, we show in Fig. 11(a) the percentage of energy saved for G_1, G_5, G_{10} when α=4, B=3, m=1. The impact is observed to be lower than that of α. Next, we show the total energy saved for varying G under the influence of α in Fig. 11(b) and Fig. 11(c) using α=3, 4, B=1, m=1. Both results



(a) (b)

Fig. 12 Varying Movement Parameter **(a)** Percentage of Energy Saving (α=4, B=3, G=10, m=1 vs. m=2) **(b)** Energy Saving Difference (α=3, B=1, G=5, m=1 vs. m=2)



(a) (b) (c)

Fig. 13 Example *REA* Paths with Various Number of Turns **(a)** Energy saved: 365.66 Joule **(b)** Energy saved: 4.95 Joule. **(c)** Energy saved: 1.47 Joule

exhibit higher energy saved over *G* and *MEA* path length. More importantly, larger α produces higher energy saving difference.

Impact of Movement Parameter, *m*. To simulate different types of robot (e.g. with different weight) and the surface of the simulated area, we study the effect of *m*. Fig. 12(a) shows that *m* has comparably little impact on *REA* path. It can be explained by referring to the energy models described in Section 3.2 that unlike *G*, *m* is not influenced by α. Meanwhile, Fig. 12(b) depicts that using lower *m* increases total energy saved by *REA* path. This is also supported by the study of the tradeoff between mobility energy and communication cost [12]. Furthermore, we observe some *REA* paths falling on *MEA* paths when the mobility energy consumed is much higher than the communication cost, resulting in zero energy savings. It occurs mostly on short *MEA* paths. Higher communication cost (higher *B* or α) is needed to compensate *m*. However, since we simulate the lowest *m*=1, our approach is applicable to all lightweight robots mentioned in Section 5.1 using $m < 1 J/m$, leading to higher energy saving than our simulation results.

Next, we show some example *REA* paths with the total energy saved in Fig. 13. The objective of this analysis is to determine if a *REA* path is worth computing. Fig. 13(a) presents a scenario that achieves a total energy saving of 365.66 Joule, representing one of the strong *REA* paths. On the other hand, the two example paths in Fig. 13(b) and Fig. 13(c) illustrate the weak *REA* paths. In the first weak path, the total energy saved is at merely 4.95 Joule but the robot needs to make three distinct turns traveling on it. The second path shows an even weaker path with more turns. Turning needs extra energy for controlling the motion of robot wheels. Let the additional energy needed to move on *REA* path be β, which includes energy to compute *REA* path and control robot wheels. If the energy saving is too low to compensate β, it is unnecessary to trigger *REA* path computation. The robot can decide if a particular turn on *REA* path is worth making in terms of its energy efficiency.

With the simulation results explained above, we show the impact of each parameter and different combination of the parameters on the performance gain of *REA* path. Overall, the total energy saved increases with higher α, G, B, the length of *MEA* path and its fragments. Higher m reduces the amount of energy saved, though its impact is less than the others. Analysis on the percentage of energy saving shows that the path loss exponent has the most significant impact. If the communication takes place in free space, the robot will always move on *MEA* path.

6 Conclusions and Future Works

In this paper, we study the energy optimization problem for an artificial mobile node in a multiple relay wireless network. We propose a novel energy-aware movement strategy that computes a minimal-energy detour by considering both the motion cost and the communication cost of a mobile node. The mobile node takes the full advantage of the optimal-energy path to prolong its lifetime while working towards its mission. By analyzing the impact of different parameters, we show the simulation results, which are promising in improving the energy efficiency of future networked robot system. For further exploration, the proposed *REA* strategy can be incorporated into other aspects, such as improving the performance of wireless communications in terms of its Quality of Service, through utilizing the benefits of controllable node mobility. Lastly, a thorough study on the trade-off between the energy and time consumption to produce an optimal path is significant to time-critical applications.

Acknowledgements This research is partially supported by *DFG-Sonderforschungsbereich SPP 1183: Organic Computing. Smart Teams: Local, Distributed Strategies for Self-Organizing Robotic Exploration Teams.*

References

1. V. Rodoplu and T. Meng, “Minimum energy mobile wireless networks,” in *Proceedings of IEEE ICC*, vol. 3, 1998, pp. 1633–1639.
2. W. Su, S. Lee, and M. Gerla, “Mobility prediction in wireless networks,” in *Proceedings of the IEEE Military Communications Conference (MILCOM)*, 2000.
3. A. Jardosh, E. Belding-Royer, K. Almeroth, and S. Suri, “Towards realistic mobility models for mobile ad hoc networks,” in *Proceedings of ACM MobiCom*, 2003.
4. *K-Team Corporation.* http://www.k-team.com, 2007.
5. *EPFL Education Robot.* http://www.e-puck.org, 2007.

6. A. Farinelli, L. Iocchi, and D. Nardi, "Multirobot systems: A classification focused on coordination," *IEEE Trans. Syst., Man, Cybern.*, 2004.
7. D. Koutsonikolas, S. M. Das, Y. C. Hu, Y.-H. Lu, and C. S. G. Lee, "Cocoa: Coordinated cooperative localization for mobile multi-robot ad hoc networks," in *the 26th IEEE ICDCSW*.
8. M. Powers, T. Balch, and B. Lab, "Value-based communication preservation for mobile robots," in *IEEE ICRA*, 2004.
9. S. M. Das, Y. C. Hu, C. G. Lee, and Y.-H. Lu, "An efficient group communication protocol for mobile robots," in *IEEE ICRA*, 2005.
10. *Swarm-robotics.org*. http://www.swarm-robotics.org/, 2007.
11. *Swarm-bots Project*. http://www.swarm-bots.org, 2007.
12. D. K. Goldenberg, J. Lin, A. S. Morse, B. E. Rosen, and Y. R. Yang, "Towards mobility as a network control primitive," in *Proceedings of the 5th ACM MobiHoc*, 2004, pp. 163–174.
13. C. Tang and P. K. McKinley, "Energy optimization under informed mobility," *IEEE Trans. Parallel Distrib. Syst.*, vol. 17, no. 9, pp. 947–962, 2006.
14. W. Liu, Y. Zhang, K. Lu, and Y. Fang, "Energy conservation through resource-aware movement in heterogeneous mobile ad hoc networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 11, no. 1, pp. 7–20, 2006.
15. C. C. Ooi and C. Schindelhauer, "Minimal energy path planning for wireless robots," in *ROBOCOMM*, 2007.
16. *Status of Project IEEE 802.11n - Standard for Enhancements for Higher Throughput*. http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm, 2007.
17. I. F. Akyildiz, T. Melodia, and K. R. Chowdhury, "A survey on wireless multimedia sensor networks," *Comput. Networks*, vol. 51, no. 4, pp. 921–960, 2007.
18. C.-H. Wang, Yu Wu, "Robot-assisted sensor network deployment and data collection," in *CIRA*, 2007, pp. 467–472.
19. Y.-C. Tseng, Y.-C. Wang, K.-Y. Cheng, and Y.-Y. Hsieh, "imouse: an integrated mobile surveillance and wireless sensor system," vol. 40, no. 6. IEEE Computer, 2007.
20. Y. Mei, Y.-H. Lu, H. Y.C., and L. C.S.G., "A case study of mobile robot's energy consumption and conservation techniques," in *12th IEEE ICAR*, 2005, pp. 492– 497.
21. Gruenewald, M., Rueckert, U., Schindelhauer, C., Volbert, K.: Directed power-variable infrared communication for the mini robot khepera. In: Proceedings of the 2nd International Conference on AMIRE, pp. 113–122 (2003)
22. A. T. Hoang and M. M., "Exploiting wireless broadcast in spatially correlated sensor networks," in *IEEE ICC*, 2005, pp. 2807– 2811.
23. *IEEE 802.11 WIRELESS LOCAL AREA NETWORKS - The Working Group for WLAN Standards*. http://www.ieee802.org/11/, 2007.