Energy Balancing for Robotic Aided Clustered Wireless Sensor Networks Using Mobility Diversity Algorithms

Daniel Bonilla Licea*, **Edmond Nurellari**‡, and Mounir Ghogho*,†

‡**School of Engineering, University of Lincoln, UK**
*International University of Rabat, FIL, TICLab, Morocco
†School of Electronic and Electrical Engineering, University of Leeds, UK

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Overview

Overview

1. Introduction

Motivation

- Monitoring a ROI is one of the most important applications of WSNs [Akyildiz 2003] and [Barbarossa 2013].
- Flexible and can be seamlessly deployed over a wide geographic area for military monitoring and surveillance purpose [Chen 2006].

Challenges

- Increase the operational lifetime of WSN deployed in a large field.
- Challenges in the design of algorithms to deal with the load imbalance among CHs.

Objective

- To improve the operational lifetime by taking advantage of the mobility diversity in a manner that:
  1. Efficiently utilizes the scarce bandwidth.
  2. Overcomes the limitations of a fading wireless channel.
  3. Minimize the CHs' transmit power.

1. Introduction

Literature Review

- Clustered WSNs has been extensively studied in various contexts such as energy management [Abbasi 2007, Wei 2011] and fusion rules design [Meng 2012, Barbarossa 2014, Nurellari 2016].

- Recent publications [Zhu 2015, Aldalahmeh 2016] propose a cluster partitioning to deal with the load imbalance among CHs.
  1. Ideal exchange of information among the SNs is assumed.
  2. Not feasible in the context of WSNs, SNs are battery operated (i.e., limited energy).
  3. Practical WSN scenarios suffer from channel impairments such as fading and attenuation.

Overview

2. Problem Formulation

Centralized Approach: with FC

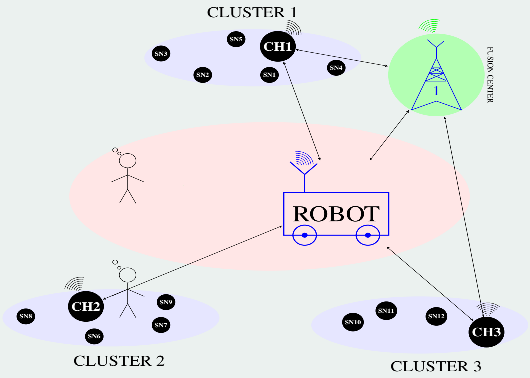

Figure 1: Schematic communication architecture among peripheral CHs, MR, and FC. The CH can communicate with the FC directly or via the MR.

2. Problem Formulation

System Model

- So, at the MR (positioned at point $\mathbf{p}(t)$), the test statistic received from the jth CH at time t is:

$$\hat{T}_j(t) = \left(\frac{s(\mathbf{p}(t), \mathbf{q}_j) h(\mathbf{p}(t), \mathbf{q}_j, t)}{\|\mathbf{p}(t) - \mathbf{q}_j\|_2^{\alpha/2}} \right) T_j(t) + n(t), \text{where } n(t) \sim \mathcal{N}(0, {\sigma_i}^2))$$

- $\mathbf{q}_j \rightarrow$ position of the jth CH, $s(\mathbf{p}(t), \mathbf{q}_j)$ represents the shadowing, modeled by a lognormal r.v., $h(\mathbf{p}, \mathbf{q}_j, t)$ represents the small scale fading

2. Problem Formulation

System Model

- For notational convenience we denote the position of the FC as $\mathbf{q}_0$.
- To satisfy a certain average reference power P_{ref} at the receiver, the CHs and the MR use transmit power control mechanism.
- At the jth CH, the average transmit power is:

$$P_j = \frac{\|\mathbf{p}(t) - \mathbf{q}_j\|_2^{\alpha} P_{ref}}{s_j^2(\mathbf{p}(t), \mathbf{q}_j) \left| h_k(\mathbf{p}(t), \mathbf{q}_j) \right|^2}$$

where $t \in [k\tau, (k+1)\tau)$, and α is the path loss coefficient.

Overview

Multiple Link Mobility Diversity Algorithm

- To extend the operational lifetime of the WSN and to deal with the imbalanced load among the CHs, we propose a $multiple - link$ mobility diversity algorithm.
- We assume that the FC, at time instant $t = k\tau$, has full knowledge of the channel gains $(h(\mathbf{q}_0, \mathbf{q}_j), \forall j = 1, 2, \ldots, N)$ from CHs to FC.
- The FC determines the L CHs with the lowest (CH-to-FC) channel gain and forward the corresponding CHs' identities to the MR.
- These communication links may significantly reduce the communication quality (due to small-scale fading) and eventually a larger amount of CH transmit power.

3. Proposed Solution

Multiple Link Mobility Diversity Algorithm

- Type of diversity technique that exploit the spatial variations of the small-scale fading and the mobility of the MRs.
- Their operation is divided in two phases:
  1. **exploration phase** (explores a series of K stopping points);
  2. **selection phase** (MR uses a selection rule to decide on the optimum position)
- We require a simultaneously small-scale fading compensation technique of $L + 1$ communication links (i.e., the L MR-to-CHs as well as the MR-to-FC links).
- To estimate the MR's next position, we develop a path planner that requires small-scale fading predictors.

3. Proposed Solution

Multiple Link path Planner

- Here, we choose the first order predictor (i.e., considers only the measurements of the channel at the current MR's position).
- The MR position at time instant t_{n+1} (i.e., $\mathbf{p}(t_{n+1})$), is chosen such that the minimum channel gain is maximized over $L+1$ links. So, our optimisation problem is:

$$\begin{aligned}&\text{maximize}_{\ell_n \in [\ell_d, \ell_u]} \quad G_1(\mathbf{p}(t_{n+1}))\\ &\text{s.t.}\\ &\mathbf{p}(t_{n+1}) = \mathbf{p}(t_n) + \ell_n [\cos(\phi_n) \quad \sin(\phi_n)]^T\end{aligned}$$

where

$$G_1(\mathbf{p}(t_{n+1})) = \mathbb{E}\left[\min_{j=0,1,\cdots,L}\left\{\frac{s_j\left|\tilde{h}(\mathbf{p}(t_{n+1}),\mathbf{q}_j)\right|}{d_j^{\alpha/2}}\right\}\right]$$

3. Proposed Solution

Multiple Link path Planner

- The small-scale fading predictor at time instant t_{n+1} given the estimate $\hat{h}(\mathbf{p}(t_n), \mathbf{q}_j)$ is [Bonilla Licea 2017]:

$$\begin{aligned}\tilde{h}(\mathbf{p}(t_{n+1}), \mathbf{q}_j) &= \rho(\mathbf{p}(t_{n+1}), \mathbf{p}(t_n))\hat{h}(\mathbf{p}(t_n), \mathbf{q}_j) \\ &+ \left(\sqrt{1 - \rho^2(\mathbf{p}(t_{n+1}), \mathbf{p}(t_n))}\right) u_{j,n}\end{aligned}$$

  where $t_{n+1} - t_n \ll \tau$,and, and $u_{j,n}$ is a set of Normal independent and identically distributed random variables for $0 \leq j \leq L$, $1 \leq n \leq K$.

- Solving this optimisation problem is computationally expensive in general $\rightarrow$ develop an alternative optimization problem which is similar but much simpler to solve.

3. Proposed Solution

Multiple Link path Planner

- The fading predictor is a complex Gaussian random variable $\rightarrow$ it can be easily shown that:

$$G_1(\mathbf{p}(t_{n+1})) = \int_0^{\infty} \Pi_{j=0}^{L} Q_1 \left(\frac{\nu_j}{\sigma_j}, \frac{x}{\sigma_j} \right) \mathrm{d}x$$

  where $Q_1(\cdot, \cdot)$ is the Marcum Q function.

- Note that each multiplicative term is a monotonically decreasing function that tends to zero. Then, there exists a value X_0 such that:

$$\int_0^{\infty} \Pi_{j=0}^{L} Q_1 \left(\frac{\nu_j}{\sigma_j}, \frac{x}{\sigma_j} \right) \mathrm{d}x \approx \int_0^{X_0} \Pi_{j=0}^{L} Q_1 \left(\frac{\nu_j}{\sigma_j}, \frac{x}{\sigma_j} \right) \mathrm{d}x$$

Multiple Link path Planner

- Using Chebyshev's inequality:

$$\frac{\int_0^{X_0} \prod_{j=0}^{L} Q_1\left(\frac{\nu_j}{\sigma_j}, \frac{x}{\sigma_j}\right) \mathrm{d}x}{X_0} \geq \frac{\prod_{j=0}^{L} \int_0^{X_0} Q_1\left(\frac{\nu_j}{\sigma_j}, \frac{x}{\sigma_j}\right) \mathrm{d}x}{X_0^L}$$

$$= \frac{1}{X_0^L} G_2(\mathbf{p}(t_{n+1}))$$

with:

$$G_2(\mathbf{p}(t_{n+1})) \triangleq \prod_{j=0}^{L} \left\{ \sigma_j \sqrt{\frac{\pi}{2}} L_{1/2}\left(\frac{-\nu_j^2}{2\sigma_j^2}\right) \right\}$$

where $L_{1/2}(\cdot)$ is Laguerre's polynomial of degree 1/2.

3. Proposed Solution

Multiple Link path Planner

- We obtain the alternative optimization problem by replacing the optimization target $G_1(\mathbf{p}(t_{n+1}))$ by its lower bound $G_2(\mathbf{p}(t_{n+1}))$:

$$\begin{aligned}
&\text{maximize}_{\ell_n \in [\ell_d, \ell_u]} \quad G_2(\mathbf{p}(t_{n+1})) \\
&\text{s.t.} \\
&\mathbf{p}(t_{n+1}) = \mathbf{p}(t_n) + \ell_n [\cos(\phi_n) \quad \sin(\phi_n)]^T
\end{aligned}$$

where ℓ_n is defined over the interval $[\ell_d, \ell_u]$ and determines the correlation between the small-scale fading terms.

3. Proposed Solution

Multiple Link path Planner

- Optimisation is performed at time instant t_n using the observed communication channel measurements at MR position ($\mathbf{p}(t_n)$).
- Solving the above optimisation problem will yield a set of stopping points with good wireless channel properties.
- The final step is to decide among those stopping points, the optimum MR position such that the overall WSN performance is improved.
- Here the MR will select this optimum stopping point such that the minimum channel gain is maximized.

Overview

4.Simulation Setup

- We evaluate numerically the performance of our proposed $multiple - link$ MDA.

- We simulate a WSN deployed in a 120×120 ROI and M SNs divided into $N = 3$ clusters with arbitrary SN geometry.

- The distances between the MR and CHs are assumed to be known.

4.Simulation Setup

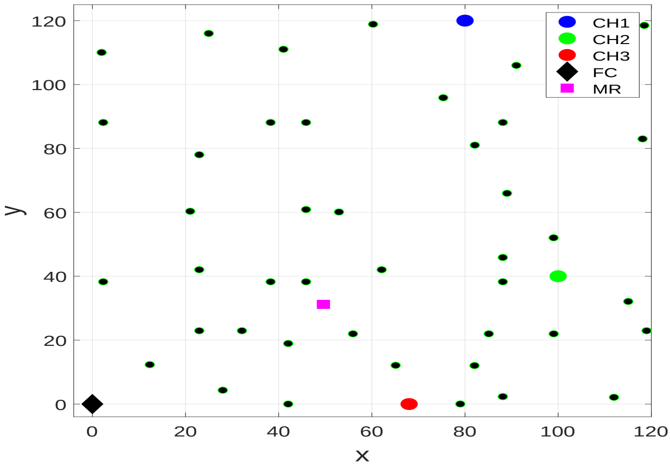

Figure 2: Spatial configuration of the WSN where the SNs are represented with green (normalized over wavelength λ).

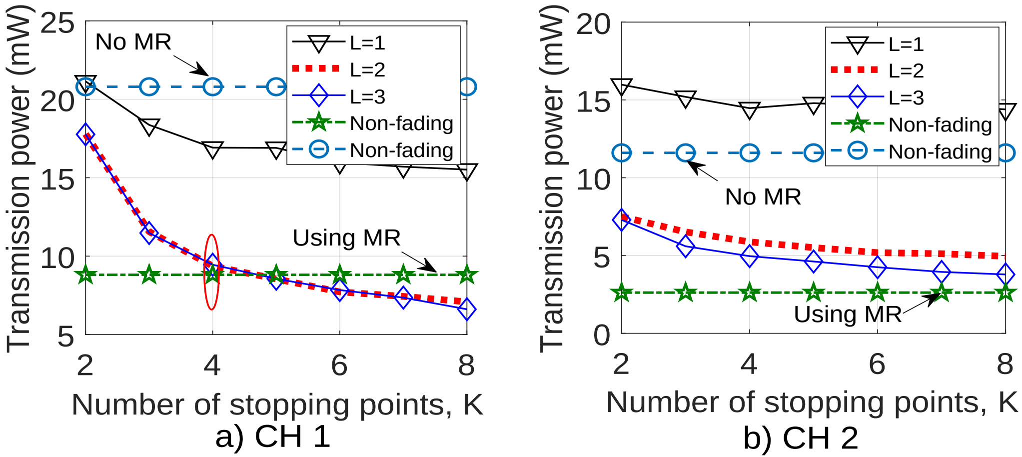

Figure 3: Average CHs transmission power in (3) versus the number of stopping points (K), parametrized on the number of CHs that use the MR as a relay (L) with $P_{ref} = 1$ μW, and $\alpha = 2$.

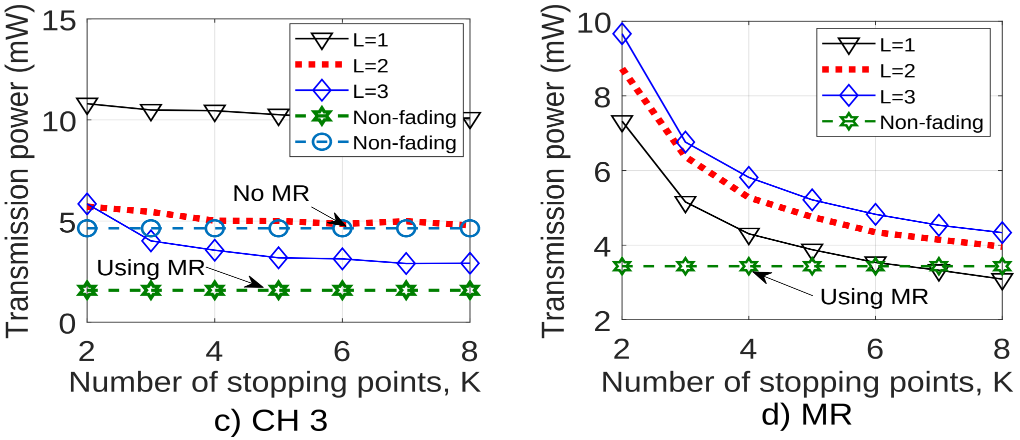

Figure 4: Average CHs transmission power in (3) versus the number of stopping points (K), parametrized on the number of CHs that use the MR as a relay (L) with $P_{ref} = 1\ \mu$W, and $\alpha = 2$.

4.Simulation Results 3/3

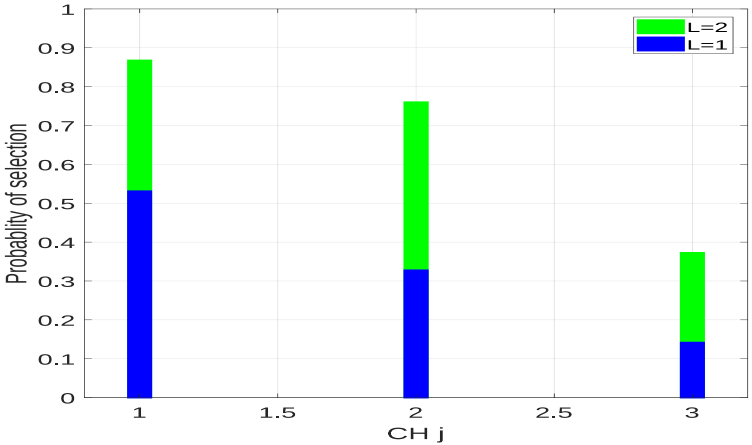

Figure 5: CH's selection probability to use the MR as a relay versus the CH (j), parametrized on the number of CHs that use the MR as a relay (L) with $P_{ref} = 1\ \mu$W, and $\alpha = 2$.

4.Spatial Configuration

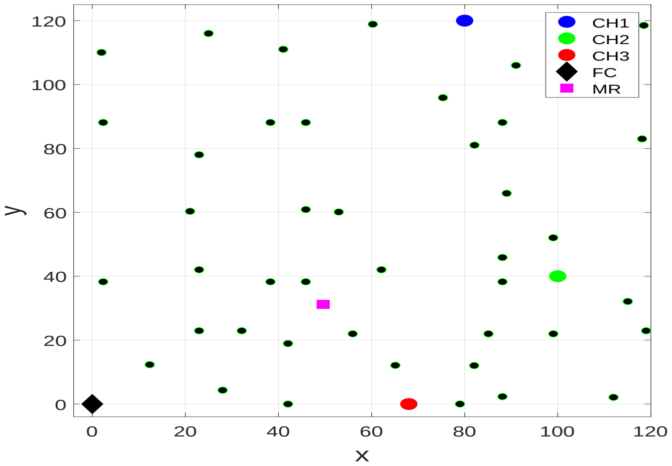

Figure 6: Spatial configuration of the WSN where the SNs are represented with green (normalized over wavelength λ).

5.Conclusions/Future Work

- We propose an efficient *multiple − link* MDA to balance the CHs energy and extend their operational lifetime in random clustered WSNs.
- We have shown how by using an MR as a relay with the proposed MDA, the CH's mean transmit power can be significantly reduced.
- Finally, we have also shown that the proposed MDA results in a lower CH's transmit power compared to the non-fading communication channel case.
- Future work will investigate the analysis of the problem for fully distributed solution (i.e., where there is no FC).

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Questions/Comments