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Cost analysis of hybrid adaptive routing protocol for heterogeneous wireless sensor network

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Abstract. This study aims to explore the impact of heterogeneity on a hybrid algorithm called Multi Adaptive Filter Algorithm by constructing series of experiments. Here, the simulations were made between 'Total Energy Spent' and 'Number of Sources' considering temporal correlation. The results were drawn from the trace information generated using 'Monte Carlo' simulation methods. After keen analysis, the results show that different levels of heterogeneity are best suited for correlated event detections. Moreover, based on the conclusions drawn, it can be safely inferred that n-level heterogeneity reduces the total energy spent close to 60%. Further, cost analysis recommends that adding progressive nodes preserves the cost factor in the bracket of 230–280$/Joule. The novel approach can immensely help the future solution providers to overcome the battery limitations of wireless sensor networks. This study provides insights into designing heterogeneous wireless sensor networks and aims at providing the cost-benefit analysis that can be used in selecting the critical parameters of the network.

Keywords. Event detection; wireless sensor networks; hybrid routing; cost benefit analysis; proactive routing; reactive routing.

1. Introduction

Routing is the most vital and energy consuming task in wireless sensor networks (WSNs). Depending on the resource divergence, WSNs can either be homogeneous or heterogeneous. Hitherto, traditional approaches were based on the assumption of energy homogeneity of the deployed nodes, yet in real life applications it is often desired to consider the heterogeneous deployments of nodes with different capabilities. In heterogeneous deployment, nodes with higher capability in terms of sensing range, communication range, additional energy, high processing power, etc. are deployed to extend the network lifetime and enhance the overall energy efficiency of the network. On the other hand, enhancing the capabilities of the deployed nodes would have a direct impact on overall cost of the network as well. This research work is based on the understanding that there could be a substantial consequence of adding heterogeneity to the network and hence, it should be explored and experimented for a better network lifetime. Additionally, we are also presenting the mathematical and simulational cost analysis of adding progressive nodes in the network as well.

The most widely used routing strategies can be categorized as reactive, proactive and hybrid. However, only hybrid routing approaches are accepted choices to deal with event dynamics. The first hybrid adaptive routing algorithm called Multi-moving average filter (Multi-MAF) for WSNs was proposed by Carlos *et al* [1]. The Multi-MAF algorithm, selects the routing strategies from traditional reactive and proactive routing approaches to deal with different traffic profiles of the network. Experiments have shown that in unpredictable network operating conditions, a hybrid routing algorithm is more energy efficient than a fixed routing strategy, leading to enhanced network lifetime. Though, the algorithm is implemented and evaluated only on the homogeneous network.

In this paper, we conduct an analysis of Multi-MAF Algorithm on heterogeneous network as it has direct applications in real life and antecedents in this context are limited to homogeneous networks. Moreover, evaluation and performance of the algorithm is questionable when both multiple levels of energy and temporal characteristics are considered. The stimulus behind is that few nodes can be loaded with extra battery energy life, thereby enhancing the overall lifetime of the network. In multi-hopping relaying to the sink, there always exists a non-uniform energy consumption in the network. Nodes adjacent to the base station become energy voids because of highest energy drainage due to relaying. Consequently, there is an understanding that the network lifetime can be enhanced if the nodes with higher drainage are embedded with high initial energy as suggested by Qing *et al* [2].

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The two foremost prospects of a WSN are lower hardware cost and constant energy drainage. Though heterogeneity aims to achieve the former, homogeneity assumes the persistent drainage of energy. Both characteristics are anticipated to be integrated within the same network. The objective of this paper is to provide the comparative analysis of homogeneous vs. heterogeneous networks along with the cost analysis to decide the energy-hardware trade off.

Furthermore, temporal correlation of real signals is one of the many statistical features which is efficaciously practiced for event detection in WSN applications as proposed by Abdur & Simon [3]. Temporal correlation regulates the coupling between the consecutive events which can either be correlated or uncorrelated. Carlos *et al* [4] suggested that Uniform and Gaussian distributions are the foremost indicators to assess the temporal characteristic of event detection. The uniform distribution, denoted by an average value of the data generated by sensors, represents the uncorrelated event detection. Correspondingly, Gaussian distribution characterizes the correlated detection which in turn is calculated by standard deviation parameter. Proposed algorithm is considered for temporal correlation-simulated for correlated and unrelated event detection.

To the best of our knowledge, presented work is one of its kind to understand the effect of heterogeneity in a hybrid routing algorithm suited for event detection applications and providing the mathematical cost analysis of the same. The novelty of the approach lies in exploring the cost-benefit analysis of heterogeneous classification of the Multi-MAF algorithm so as to discover its effect on different profiles of traffic.

The outline of the paper is as stated: section 2, our problem statement is framed. Section 3 briefly details the relevant studies that are closest to our work. Section 4 outlines the working of Heterogeneous-multi adaptive filter (H-MAF). Section 5 establishes the cost analysis. Simulation and performance evaluation is done in section 6. To finish, we present the conclusions drawn from this research work.

2. Problem statement

The problem attempts to investigate the effect of heterogeneity on Multi-MAF, implemented on different energy levels so that the effect of heterogeneity as an optimization technique could be explored. Recent advances in this context have elaborated numerous optimization practices which could ease battery consumption thereby enriching network lifetime as stated by Eduardo *et al* [5]. These practices are based on the uniform consumption of battery by all the nodes. But, the consumption depends upon various factors viz. network type, radio coverage, distance to the sink, routing strategy, etc. as analyzed by Gregory & William [6]. The problem statement revolves around analyzing the different energy levels reliant upon their consumption and questioned for better resource consumption. A cost analysis is required to be carried out in order to substantiate the argument. The problem can be detailed as below:

Sub-problem 1: Our problem revolves around the classification of nodes as normal ('Nn'), advanced ('Na') and super ('Ns') nodes for the simulation of Multi-MAF for heterogeneous network.

Assumption : Each node has same communication and sensing model.

Sub-problem 2: To obtain the cost analysis of the heterogeneity. The Energy cost of a sensor node $= a + \beta E$ where 'α' is the hardware cost, 'β' is the constant and 'E' is the battery energy of the normal node. $E_k = \sum_{k=1}^{n} k\,(a_k + \beta E_k)$ where 'k' denotes the selected heterogeneity levels respectively. 'E_k' denotes the different selected energy level of nodes correspondingly.

Assumption : Battery costs are not included in the hardware cost.

3. Related work

As mentioned in section 2, 'heterogeneity' is the major criteria for exploring the context of the problem. In this section, a discussion is laid on different aspects of it, worked by contemporary researchers. Basu Dev *et al* [7] suggested that proactive and reactive strategies are linked with different costs in terms of energy consumed. The selected protocol must satisfy the system needs and it should not require excessive resources. Carlos *et al* [1] achieved energy efficiency in Multi-MAF by adopting the routing strategy autonomously in different network conditions. The research work concludes that the hybrid strategies are more suitable than the fixed reactive and proactive strategies. Carlos *et al* [1] suggested that hybrid routing is the best possible solution for varying network conditions as these provide a better adoption strategy. In MANETs, Zygmunt & Marc [8] proposed ZRP and Ramasubramanian *et al* [9] proposed SHARP but these are not directly considered for WSNs due to the difference in the basic nature of both types of networks. Ramasubramanian *et al* [9] proposed an adaptive dynamic hybrid routing algorithm and concluded that hybrid not only balances energy but also improves quality parameters. Ahmed *et al* [10] suggested that a hybrid routing algorithm can be used for extending the lifetime of WSNs.

Heterogeneous WSNs consist of sensor nodes equipped with different abilities like computing power, sensing range, and energy efficiency. Vivek *et al* [11] concluded that heterogeneous networks are more suitable than the homogeneous counterpart for real life applications. Hence, heterogeneity in WSN is an emerging area of research. Georgios *et al* [12] implemented SEP for heterogeneous networks and found to yield longer stability because of energy heterogeneity. Harneet & Ajay [13] implemented HEED for heterogeneous network and evaluated to enhance the network lifetime. Dilip *et al* [14] provided an in-depth analysis of heterogeneous network with respect to the energy efficiency and the network lifetime.

A hierarchical cluster-based protocol is developed to analyze the network lifetime and deployment cost of the network by Dilip *et al* [14]. Further, Romer *et al* [15] discussed the consequences of the requirements of hardware issues and software support regarding design space of the networks.

4. How H-MAF: Heterogeneous-moving average filter routing works

This section illustrates the working of H-MAF: a Heterogeneous-Moving Average Filter routing algorithm for heterogeneous network based on nodes having dissimilar energy. The H-MAF solution regulates the network behavior depending on the network scenarios. Care has been taken to present it at the component level in terms of constituting algorithms, event detection, and an equation model to achieve heterogeneity.

1. *Proactive component:* H-MAF implements Earliest-First (EF) Tree for proactive routing component. The tree is built by the sink node by sending a control packet to all the neighbors. Receiving node, after receiving the control packet, saves the address of the sender as a parent and then the process is repeated further to other neighbors. Once the sensor node has data to send, it will transmit to its parent node.
2. *Reactive component:* H-MAF implements Source Initiated Dissemination (SID) as a reactive routing strategy. In this, the sensor node that detects the event transmits the data to all its neighbors. Receiving node stores and forwards the first packet received and discards the rest. When the sink node finally receives the data, it will send a control message to the node from where it receives the data first. The node will update its table so that it knows the parent node in future. Once the event stops, the table expires and the network becomes inactive again.
3. *Hybrid component:* H-MAF is the hybrid of EF Tree and SID depending on the network conditions. Initially, H-MAF is in reactive state and it turns into proactive state as soon as it receives a tree build message from the sink. It will turn back to SID after a time-out.
4. *Adaptation:* H-MAF change from reactive to proactive strategy depending on the event characteristics. Event estimation is done using Moving Average Filter. H-MAF uses this filter, which calculates the mean of the inputs to decide the routing strategy to be followed in the network.
5. *Event detection model:* The model is used to represent two types of detections namely: uncorrelated and correlated event detections. These detections are represented by uniform and Gaussian distributions respectively. In a uniform distribution, participating nodes are assumed to generate data randomly and hence represent uncorrelated event detection. Correlated event detections are distributed with a standard deviation time.
6. *Heterogeneous equation model:* The classification of levels of heterogeneity is reliant on additional energy assigned to the nodes. Heterogeneous equation model is based on the assumption that a fraction of nodes are enriched with additional energy than the rest of the nodes. Three levels of heterogeneity are considered. In 2-level heterogeneous WSN, the nodes are classified as advanced and normal nodes. Similarly, 3-level heterogeneous WSN tags nodes as super nodes, advanced nodes, and normal nodes. However, random distribution of energy is applied in a multilevel heterogeneous network. The consequence of putting into practice divergent energy levels is measured (table 1).

For 2-level heterogeneous network, initial energy is given by

$$E_{total} = N * (1 - m) * E_0 + N * m * E_0 * (1 + \alpha)\,. \quad (1)$$

Effectively, this heterogeneous network has 'αm' more nodes amounting to 'αm' times additional energy in the network.

For 3-Level heterogeneous network, the total energy of the network is

$$\begin{aligned} E_{total} \;=\; & N * (1 - m) * E_0 + N * m * (1 + m_o) \\ & * E_0 * (1+\alpha) + N * m * m_o * E_0\,(1+\beta)\,. \quad (2) \end{aligned}$$

$$E_{total} = N * E_0 * (1 + m * (\alpha + m_o * \beta))\,. \quad (3)$$

In multilevel heterogeneous WSN, random energy level of sensor nodes is determined from a close-set [E, E*(1−$\alpha_{\max}$)], where 'E' is the lower bound and '$\alpha_{\max}$' determine the value of the maximum energy. Initially, the node 's_i' is equipped with an initial energy of '$E_0 * (1 + \alpha_i)$', which is 'α_i' times more energy than 'E_0'. Hence, the total network energy is given by

$$E_{total} = \sum\nolimits_{i=1}^{n} E_0 * (1 + \alpha_i)\,. \quad (4)$$

$$E_{total} = E_0 * \sum\nolimits_{i=1}^{n} (1 + \alpha_i)\,. \quad (5)$$

Table 1. Heterogeneity parameters.

Variable	Notation
Number of sensors deployed	N
Fraction of super nodes	m_0
Fraction of advanced nodes	m
Fraction of normal nodes	$1 - m$
Total number of super nodes	$N^*m^*m_0$
Total number of advanced nodes	$N^*m^*(1 - m_0)$
Initial energy of the normal nodes	E_0
Extra energy in the advanced nodes	α
Extra energy in the super nodes	β
Energy of each super node	$E_0(1 + \beta)$
Energy of each advanced node	$E_0(1 + \alpha)$

5. Cost analysis

In this paper, heterogeneous nodes are classified as: Normal (‘N_n’), Super (‘N_s’) and Advanced (‘N_a’) nodes. All the three types of nodes are using the deterministic sensing model proposed by Ming *et al* [16] but the sensing range of super nodes is higher than that of advanced nodes. In this model, an event is detected if the strength of the received signal is within the sensing threshold set for event detection. For communication model, first order radio model as proposed by Wendi *et al* [17] is used.

The default communication and the sensing range of ‘N_n’, ‘N_s’, and ‘N_a’ are defined as ‘R_{cn}’, ‘R_{sn}’ and ‘R_{cs}’, ‘R_{ss}’ and ‘R_{ca}’, ‘R_{sa}’ respectively. The underlying assumption for the communication and sensing range is ‘$R_{ca} > R_{cs} > R_{cn}$’ and ‘$R_{sa} > R_{ss} > R_{sn}$’. The sensor node cost is determined by communication range and sensing range of sensor as suggested by Chun-Hsien Wu & Yeh-Ching Chung [18]. This is evaluated as the extra cost of high power sensors per unit energy savings done by that particular level of the network.

$$Energy_{saving} = (Energy_{initial} - Energy_{consumed}), \quad (6)$$

where $Energy_{saving}$ is defined as the remaining energy in the network.

For 2-level Heterogeneous Model as proposed by Curt *et al* [19], Cost for sensor node deployment $(D\_Cost_{2-level})$ can be defined from deployment cost model as follows:

$$D\_Cost_{2-level} = \frac{\left(Num\ (N_s) * N_{s\_cost} + Num\ (N_n)\right)}{Energy_{saving}} \quad (7)$$

$$N_{s\_cost} = \frac{\left(R_{cs} + R_{ss}^2\right)}{\left(R_{cn} + R_{sn}^2\right)}, \quad (8)$$

where $D\_Cost_{2-level}$ is evaluated as the total cost of deployed nodes per unit energy saving realized from the deployment of higher level nodes. N_{s_cost} is the difference of additional cost incurred by super nodes as compared to normal nodes. Cost factor as suggested by Duarte-Melo & Mingyan [20] is defined by two factors only viz. communication range and sensing range represented by ‘R_{cs}’ and ‘R_{ss}^2’ respectively as rest all the parameters are assumed to be same.

For 3-level Heterogeneous Model, Deployment cost of sensor nodes can be derived from three types of nodes as follows:

$$D\_Cost_{3-level} = \frac{\left(Num\ (N_a) * N_{a\_cost} + Num\ (N_s) * N_{a\_cost} + Num\ (N_s)\right)}{Energy_{saving}} \quad (9)$$

$$N_{a\_cost} = \frac{\left(R_{ca} + R_{sa}^2\right)}{\left(R_{cn} + R_{sn}^2\right)}, \quad (10)$$

where N_{a_cost} is the diference between advanced nodes and normal nodes.

Table 2. Simulation parameters.

Parameters	Notations	Values
Length	L	100m
Breadth	B	100m
Number of nodes	N	100
Energy consumed to transmit	E_t	50nJ/bit
Energy consumed to receive	E_r	50nJ/bit
Energy consumed by the amplifier for short distance	E_s	0.0013 pJ/bit/m^4
Energy consumed by the amplifier for longer distance	E_l	10pJ/bit/m^2
Data aggregation energy	E_{total}	5nJ/bit/signal
Message size	M	4000 bits
Initial energy	E_0	0.5J
Simulation time	T	4000 s

For n-level Heterogeneous model, ‘n’ random number of levels are defined. Hence, the deployment costs are derived as follows:

$$D\_Cost_{n-level} = \frac{\sum_{i=4}^{i=n} Num\ (N_i) * N_{i\_cost}}{Energy_{saving}} \quad (11)$$

$$N_{i\_cost} = \frac{\sum_{a=1}^{n}\left(R_{ca} + R_{sa}^2\right) + \sum_{s=1}^{n}\left(R_{cs} + R_{ss}^2\right)}{\sum_{i=1}^{n}\left(R_{ci} + R_{si}^2\right)}. \quad (12)$$

6. Simulation and evaluation

In this section, a detail description of the evaluation strategy is given. This section starts with parameters table used in the simulation. Then, a comparative analysis is demonstrated. The last part of this section shows the cost analysis. For cost analysis, the underlying assumption of the cost of advanced nodes is ‘$3x$’, super nodes is ‘$2x$’ where ‘x’ is the cost factor of normal nodes. In this paper, the research scope is limited to three types of nodes (table 2).

The case is presented with respect to normal nodes. For n-level, energy assigned to every node in the network is a random value between a closed set [0.5, 2] (table 3).

6.1 *Performance metrics and evaluation*

Total energy spent for correlated event detection. Correlated event detection is assumed if the data generated

Table 3. Configuration of heterogeneous network.

	Configuration of advanced nodes		Configuration of super nodes	
Type of network	Fraction	Additional energy	Fraction	Additional energy
2-Level	0.3(30%)	1.5(150%)	0(0%)	0(0%)
3-Level	0.3(30%)	1.5(150%)	0.2(20%)	3(300%)
n-Level	n_1	m_1	n_2	m_2

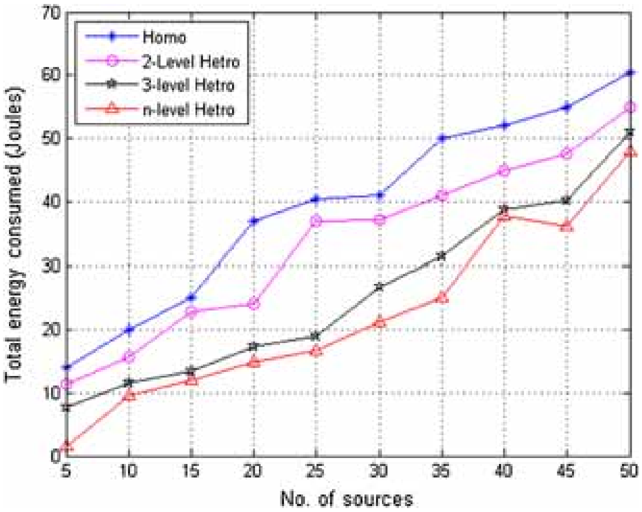

Figure 1. Total energy spent for correlated event detection.

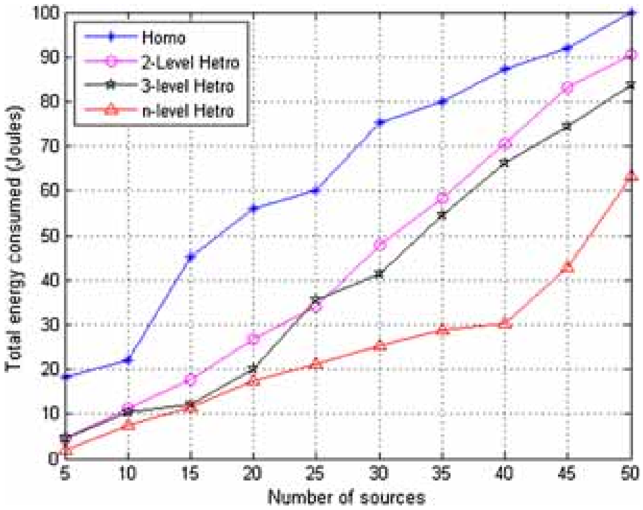

Figure 3. Total energy spent for uncorrelated event detection.

by the source nodes follow the Gaussian distribution. Total energy spent is considered to be the sum of energy consumed in sending and energy spent in receiving the packets. An increment of power consumption with the higher number of sources is depicted in the graph. Figure 1 depicts that maximum energy consumption for homogenous is 61 Joules which is almost double to 39.9 Joules consumed by the n-level heterogeneous network. two-level and 3-level stay almost in the range of 50–55 Joules.

Cost analysis. Cost comparison is done as a factor of deployment cost per unit energy saving. Deployment cost is directly proportional to the number of higher node configuration. An analysis is done to associate the energy saving per unit cost increment. The graph depicts that deployment cost of 3-level is highest i.e. 375 $/Joule. N-level and Homogeneous network depict the same cost incurred in the network (figure 2).

Total energy spent for uncorrelated event detection. For, uncorrelated event detection, different sources are generating data randomly based on the uniform distribution. Hence, an average value of random data generated over the simulation time is considered. n-level heterogeneous network performs 137% better than the homogeneous counterpart. Figure 3 shows that 2-level shows a modest performance by 29%. Three-level achieves 42%. The significant performance of heterogeneity is attributed to the fact that events are assumed to be unrelated and hence the drainage of energy cannot be predicted.

Cost analysis. For uncorrelated event detection, homogenous and 2-level incurred same cost. Three-level is the most

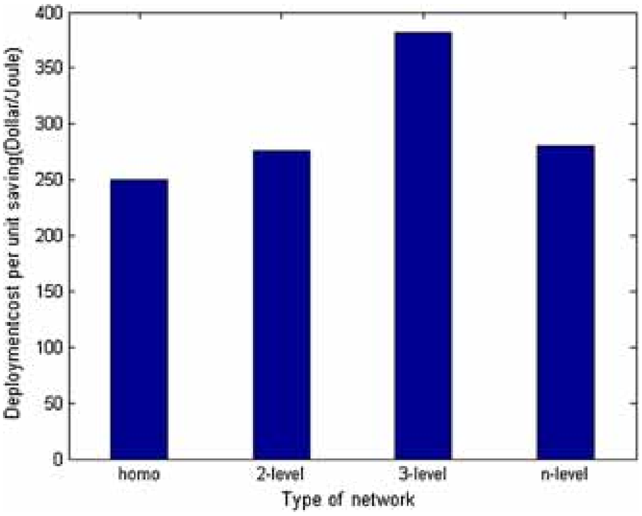

Figure 2. Cost analysis for correlated event detection.

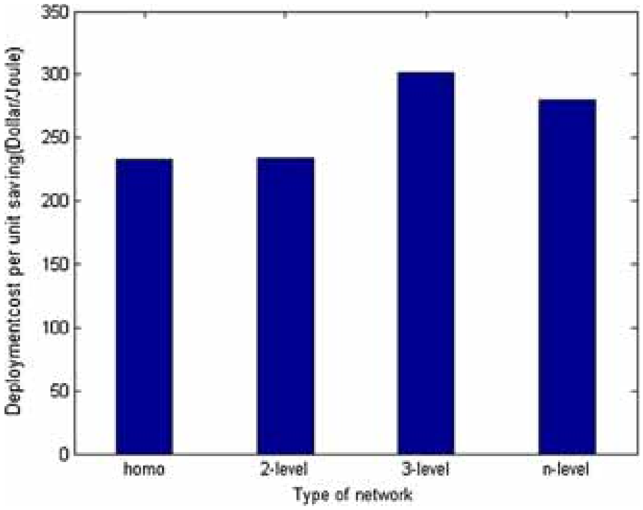

Figure 4. Cost analysis for uncorrelated event detection.

expensive of all. N-level incurred cost almost in the same bracket of [230–280 $/Joule] (figure 4).

7. Conclusion

This paper analyzes the effect of energy heterogeneity on Multi-MAF. Two temporal correlation models are considered: correlated and uncorrelated event detection. In summary, we can state that heterogeneity achieves better performance than homogenous Multi-MAF. The increased cost is also moderate equated to the energy savings.

(1) Experiments are conducted to simulate heterogeneous Multi-MAF algorithm using multiple levels of heterogeneity. The result shows that n-level performed 36% better for correlated event detection. For uncorrelated event detection, the performance reaches a maximum of 137%.

(2) Cost analysis shows that n-level incurred the cost in the same bracket as the homogeneous network for uncorrelated event detection. Three-level heterogeneity incurred the maximum cost. Hence, it is viable to infer that a random selection of heterogeneous nodes provides the optimal solution for energy saving problem.

8. Future scope

As future work, we intend to explore more heterogeneity parameters like computation, node capacities. Spatial correlation of events should be explored along with heterogeneity.

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