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Traffic and Energy Aware Routing for Heterogeneous Wireless Sensor Networks

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***Abstract*— The energy-efficiency of routing algorithm is crucial for improving the lifetime of battery constrained Wireless Sensor Networks (WSNs). The consideration of nodes heterogeneity in routing is essential for achieving optimal resource utilization. This letter considers sensor nodes with random initial energies and random disparities in data generation rate (traffic) to model a realistic clustering based WSN suited for heterogeneous sensing applications. The letter presents an energy model for the scenario and proposes a Traffic and Energy Aware Routing (TEAR) scheme to improve the stability period. The simulation results indicate that TEAR outperforms other clustering based routing algorithms under the scenario.**

***Index Terms*— Wireless sensor networks, routing protocols, heterogeneity, clustering, stability period**

I. Introduction

Internet of Things (IoT) envisions interoperability of heterogeneous devices to support diverse applications, and the Wireless Sensor Network (WSN) technology is an important building block of IoT sphere. Consideration of heterogeneity (e.g., energy, link and computational heterogeneities) [1] can improve the performance of WSN routing algorithms in terms of network lifetime, stability, reliability, network delay, etc. The energy heterogeneity in WSN routing is pursued widely; however, the link and computation heterogeneities, which are generally used along with the energy heterogeneity, are relatively less explored areas.

In the early work in WSN routing algorithms for energy heterogeneous scenarios, Stable Election Protocol (SEP) [2] considers two-level energy heterogeneity in Low-Energy Adaptive Clustering Hierarchy (LEACH) [3] like cluster-head (CH) role rotation environment. SEP proposes weighted election probabilities based on the initial energies of the nodes to give energy-rich nodes more chances of becoming CHs. The Distributed Energy-Efficient Clustering (DEEC) [4] considers multi-level energy heterogeneous WSN and prefers nodes with higher initial energy and residual energy for CH role.

The heterogeneity in terms of disparities in data generation rate (traffic) is considered under computation heterogeneity [5]. Sharma et al. [6] analyzed the effect of traffic heterogeneity in homogeneous WSN routing (LEACH) algorithm. Energy Dissipation Forecast and Clustering Management (EDFCM) [5] considers traffic heterogeneity along with energy heterogeneity in a very specific two-level WSN. Further, EDFCM considers additional nodes (management nodes) to control the number of clusters, which makes its natural distributed localized decision-making behavior questionable. The consideration of traffic heterogeneity along with energy heterogeneity is crucial for modeling realistic WSNs with application heterogeneity and event-driven scenarios.

This letter considers both, energy and traffic heterogeneities, with multiple random levels. An energy model is presented for the multi-heterogeneity scenario, where consideration of multi-level traffic heterogeneity is a novel concept. A novel routing algorithm named Traffic and Energy Aware Routing (TEAR) is presented, which considers node's traffic requirements along with its energy levels while making CH selection. TEAR shows improvements in terms of stability period (reliable lifespan of the WSN before the death of its first node) over existing algorithms (LEACH, SEP and DEEC) under the scenario.

The rest of this letter is arranged as follows. Section II presents the system model, which includes the energy model for the multi-heterogeneous scenario. In Section III, the proposed routing algorithm is described. The simulation results have been discussed in Section IV. Finally, Section V concludes the letter.

Manuscript received February 15, 2018; revised April 15, 2018; accepted May 15, 2018.

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II. System Model

Considering the basic radio model [3], the transmitter (Tx) considers energy dissipation in the radio electronics and the power amplifier, and the receiver (Rx) considers the radio electronics dissipation. The energy spent in transmitting an m_i-bits message over a distance d is given by

$$E_{Tx}(m_i, d) = \begin{cases} m_i.E_{ele} + m_i.\epsilon_{fs}.d^2 & if\ d < d_0 \\ m_i.E_{ele} + m_i.\epsilon_{mp}.d^4 & if\ d \geq d_0 \end{cases} \quad (1)$$

Where E_{ele} is the electronic circuit's per bit energy dissipation of the transmitter or the receiver, and the per bit energy dissipation in transmitter amplifier is represented by $\epsilon_{fs}.d^2$ or $\epsilon_{mp}.d^4$ depending on the free space or the multipath transmitter amplifier model respectively (based on $d_0 =$

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$\sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}}$). ϵ_{fs} and ϵ_{mp} are fixed radio parameter related to Tx amplifier's energy dissipation in free space and multipath scenarios respectively. The energy dissipated in receiving an m_i-bits message is given by

$$E_{Rx}(m_i) = m_i . E_{ele} \quad (2)$$

Considering the clustering based approach [2-6], with N heterogeneous nodes uniformly distributed (spatially) in a square region ($R \times R$). The base-station/sink (BS) is located at the centre of the region [2, 4, 5] and all the nodes are within a range of distance d_0 (free space model) from the BS. The nodes send their data to their respective CH, which aggregates the member nodes' data and forwards the aggregated message to the BS.

The initial energies of the nodes are randomly distributed over $[E_0, E_0(1+\alpha_{eh})]$ to represent a realistic energy heterogeneous deployment, where E_0 is the lower bound and α_{eh} is the energy heterogeneity factor controlling the upper bound. The total initial energy of the WSN is given by

$$E_{Tot} = \sum_{i=1}^{N} E_0\left(1+\alpha_{eh_i}\right) \quad (3)$$

Where α_{eh_i} is the energy heterogeneity factor for node i.

Further, to support heterogeneous sensing/computing requirements in terms of data-generation/traffic (i.e. the number of bits in data-messages), the data-message length of the node i with traffic heterogeneity factor α_{th_i} is given by $m_i = m_0\left(1+\alpha_{th_i}\right)$, which is randomly distributed over $[m_0, m_0(1+\alpha_{th})]$, where m_0 is the lower bound and α_{th} is the traffic heterogeneity factor controlling the upper bound. It is assumed that the system fulfils the bandwidth requirements to support such heterogeneity.

Based on [2-4], for uniformly distributed nodes the average distance between the cluster member nodes and the CH (d_{toCH}), and the average distance between the CHs and the BS (d_{toBS}) are given by

$$d_{toCH} = \frac{R}{\sqrt{2\pi k}} \quad (4)$$

$$d_{toBS} = 0.765\,\frac{R}{2} \quad (5)$$

Where k represents the number of clusters. Based on [3], the total energy dissipated in one round is given by

$$E_{Round} = k\left(E_{CH} + \left(\frac{N}{k}-1\right) E_{nonCH}\right) \approx k.E_{CH} + N.E_{nonCH} \quad (6)$$

Where E_{CH} and E_{nonCH} are energies dissipated in a CH node and a non-CH node respectively. The energy dissipated in N non-CH nodes in a round is given by

$$N.E_{nonCH} = \sum_{i=1}^{N}(m_i.E_{ele} + m_i.\epsilon_{fs}.d_{toCH}^2) = m_0(E_{ele} + \epsilon_{fs}.d_{toCH}^2)(N + \textstyle\sum_{i=1}^{N}\alpha_{th_i}) \quad (7)$$

Considering (4), (7) and $\alpha_{Tot} = \sum_{i=1}^{N}\alpha_{th_i}$

$$N.E_{nonCH} = m_0(N+\alpha_{Tot})(E_{ele} + \epsilon_{fs}\frac{R^2}{2\pi k}) \quad (8)$$

Considering the CH aggregated message which is sent from any CH to the BS is $m_{max} = m_0(1+\alpha_{th})$ bits long. The energy dissipated in the k CH nodes in one round in receiving $N-k$ member nodes data, aggregating the information and transmitting k CHs data to the BS is given by

$$k.E_{CH} = \sum_{i=1}^{N-k}(m_i.E_{ele}) + \sum_{i=1}^{N}(m_i.E_{DA}) + \sum_{i=N-k}^{N}\left(m_{max}.E_{ele} + m_{max}.\epsilon_{fs}.d_{toBS}^2\right) \quad (9)$$

Where E_{DA} is per bit energy spent in data aggregation. Considering $\sum_{i=1}^{N-k}\alpha_{th_i} \approx \frac{N-k}{N}\sum_{i=1}^{N}\alpha_{th_i} \approx \frac{N-k}{N}\alpha_{Tot}$, then

$$k.E_{CH} = \frac{N-k}{N}m_0(N+\alpha_{Tot})E_{ele} + m_0(N+\alpha_{Tot})\,E_{DA} + k.m_0(1+\alpha_{th})E_{ele} + k.m_0(1+\alpha_{th})\epsilon_{fs}.d_{toBS}^2 \quad (10)$$

Based on (6), (8) and (10), the total energy dissipated in one round is given by

$$E_{Round} = \frac{N-k}{N}m_0(N+\alpha_{Tot})E_{ele} + m_0(N+\alpha_{Tot})\,E_{DA} + k.m_0(1+\alpha_{th})E_{ele} + k.m_0(1+\alpha_{th})\epsilon_{fs}.d_{toBS}^2 + m_0(N+\alpha_{Tot})(E_{ele} + \epsilon_{fs}\frac{R^2}{2\pi k}) \quad (11)$$

The optimal number of clusters per round (k_{opt}) can be calculated by finding the derivative of E_{Round} (11) with respect to k and setting it to zero.

$$k_{opt} = k = \sqrt{\frac{N(N+\alpha_{Tot})\epsilon_{fs}.R^2}{2\pi(\,(N.\alpha_{th}-\alpha_{Tot})E_{ele}+N(1+\alpha_{th})\epsilon_{fs}.d_{toBS}^2)}} \quad (12)$$

In the absence of traffic heterogeneity, $\alpha_{th} = \alpha_{Tot} = 0$, then

$$k_{opt} = \sqrt{\frac{N.R^2}{2\pi(d_{toBS}^2)}} = \sqrt{\frac{N}{2\pi}}\,\frac{R}{d_{toBS}} \quad (13)$$

Which is the optimum number of clusters for a non traffic heterogeneous WSN [2]. Further based on (12) and (13), the value of k_{opt} is lesser for traffic heterogeneous scenarios.

III. Proposed Routing Algorithm

This section first discusses in brief the effects of energy and traffic heterogeneities, which provides insight for an effective CH selection in multi-heterogeneity scenario. Then, the proposed routing protocol is presented, which considers nodes' initial energy, residual energy and traffic load along with the average energy of the round during CH selection.

A. *Traffic and Energy Heterogeneities in WSN*

An increase in traffic heterogeneity, by increasing nodes' packet lengths, increases the effective number of bits per round for communication. This increases the WSN energy consumption per round and reduces the WSN lifetime (and the stability period). The effect is discussed further in Section IV based on simulation results.

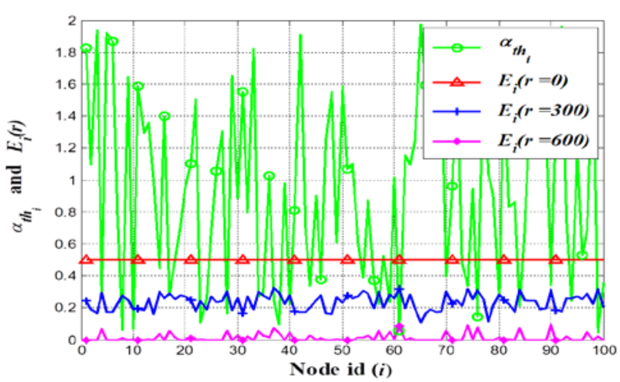

Fig. 1. Energy consumption pattern of traffic heterogeneous nodes

The nodes residual energies are analyzed over the WSN lifetime for different traffic heterogeneous scenarios (i.e. for different $\alpha_{th}$with $\alpha_{eh} = 0$). Fig. 1 shows the energy

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consumption pattern over the rounds of operation for a traffic heterogeneous scenario ($\alpha_{th} = 2; \alpha_{eh} = 0$) in DEEC environment. $E_i(r)$ is the residual energy of node i for the round r. It shows that the nodes with higher traffic load (i.e. higher α_{th_i}) lose their energies faster in comparison to the nodes with lower traffic loads over the rounds of operation.

Under two-level energy heterogeneous WSN, SEP performs better than LEACH by preferring nodes with higher initial energy for CH role. DEEC performs better than LEACH and SEP under multi-level energy heterogeneous WSN by preferring nodes (for CH role) with higher initial and residual energies over the average energy of the round.

B. Traffic and Energy Aware Routing (TEAR)

The CH selection in TEAR is based on the CH role rotation approach [2-4], where the node i becomes a CH in the current round r, if the random number selected by the node i is less than the threshold *T(i, r)*.

$$T(i,r) = \begin{cases} \frac{p_i(r)}{1-p_i(r)(r \bmod \frac{1}{p_i(r)})} & if \quad node\ i \in G(r) \\ 0 & otherwise \end{cases} \qquad (14)$$

Where $p_i(r)$ is the CH selection probability for node i during round r. $G(r)$ is a set of eligible nodes for the round r, where the rotating epoch for node i to become eligible again is $1/p_i(r)$. DEEC considers randomly distributed energy heterogeneity and prefers nodes with higher initial and residual energies for CH role, i.e. an energy-rich node has higher $p_i(r)$ and higher chances of becoming CH. As the operations of a CH are energy intensive, preferring nodes with higher initial energies and higher residual energies improves the life of energy weaker nodes and hence it improves the WSN stability period. Section IIIA discusses that an increase in traffic loads increases the effective number of bits to be communicated to the BS and hence increases network energy consumption. In traffic heterogeneous scenario, the rate of energy consumption is higher for the nodes with higher traffic loads. So, it is logical that such nodes should be avoided for energy intensive operation, e.g., CH role. For a realistic WSN model, with the nodes having heterogeneous initial energies and data traffic requirements, the proposed algorithm (TEAR) prefers the nodes with higher energies (initial and residual) and avoids the nodes with higher traffic loads for CH role. In TEAR, the probability of becoming CH for node i during round r is defined as

$$p_i(r) = \frac{p_{opt}.N(1+\alpha_{eh_i})\, N(1+\alpha_{th}-\alpha_{eh_i})E_i(r)}{(N+\sum_{i=1}^{N}\alpha_{eh_i})(N+N\alpha_{th}-\alpha_{Tot})E_{Avg}(r)} \qquad (15)$$

Where $E_{Avg}(r)$ is average energy of the round and p_{opt} is optimal probability of a node to become CH, given by $p_{opt} = \frac{k_{opt}}{N}$. The remaining functionality of TEAR is similar to DEEC. Further, in the absence of traffic heterogeneity, TEAR falls back to DEEC behaviour. Based on DEEC, the $E_{Avg}(r)$ is given by

$$E_{Avg}(r) = \frac{1}{N} E_{Tot}\left(1 - \frac{r}{R}\right);\ where\ R = \frac{E_{Tot}}{E_{Round}} \qquad (16)$$

Where R is the estimated value of network lifetime in terms of the number of rounds based on uniform energy drainage in each round. In actual scenario, the network energy may not drain in a uniform manner and few nodes remain alive for $r > R$. Based on (16), when r approaches R, $E_{Avg}(r)$ becomes a very small quantity and for $r > R$ it becomes a negative quantity. In DEEC, R is considered 1.5 times of the estimated value to avoid the situation where the last few remaining nodes stay alive and do not form clusters. Many approaches have been proposed in the literature to improve the accuracy of estimated energy per round, e.g., SEARCH [7] considers a semi-centralized approach, where BS keeps track of alive nodes and their residual energies to estimate the average residual energy of the network over the rounds of operation. This letter focuses on heterogeneity aspects and a simple approach is applied to handle the scenario. The $E_{Avg}(r)$ is considered as the value $E_{Avg}(0.9R)$ for the rounds $r > 0.9R$ to ensure active participation of remaining nodes in cluster formation for the remaining rounds. This is a better approach for distributed decision-making as nodes are aware of R and it can handle the scenarios, where r is much greater than R. The values of E_{Tot} and R are calculated and supplied (through BS broadcast message or node's initial settings) to the nodes before the beginning of WSN operations.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Number of sensor nodes (N)	100
WSN Area ($R \times R$)	100*m* x 100*m*
Initial energy lower bound (E_0)	0.5*J*
Energy consumed in Tx/Rx electronics (E_{ele})	50 *nJ/bit*
Tx Amplifier energy dissipation in free space scenario (ϵ_{fs})	10 *pJ/bit/m*^{2}
Tx Amplifier energy dissipation in Multipath scenario (ϵ_{mp})	0.0013 *pJ/bit/m*^{4}
Energy consumed in Data Aggregation (E_{DA})	5 *nJ/bit/signal*
Packet length lower bound (m_0)	4000 *bits*

IV. RESULTS AND DISCUSSION

The simulation setup considers 100 nodes (N), with randomness in energy and traffic levels, deployed uniformly in a 100*m* x 100*m* ($R \times R$) area with BS located at the centre of the region. The system model for the multi-heterogeneity approach is based on Section II. All the scenarios have been simulated in MATLAB and the simulation parameters are detailed in TABLE I. LEACH and SEP have been modified to support multi-level energy heterogeneity based on [4]. Further, the algorithms are customized to support energy consumption in multi-level traffic heterogeneity, where nodes consider their specific traffic and the aggregated message sent from CH to BS is m_{max} bits long. To handle the traffic heterogeneity in DEEC, it has been extended based on the above sections (except the proposed probability function for TEAR).

Fig. 2 shows the effect of multi-level traffic heterogeneity on LEACH, SEP and DEEC algorithms in the multi-level energy heterogeneous scenario. An increase in node packet size (from $\alpha_{th} = 0$ to $\alpha_{th} = 2$), while maintaining the energy heterogeneity ($\alpha_{eh} = 3$), deteriorates the stable region of all the three algorithms.

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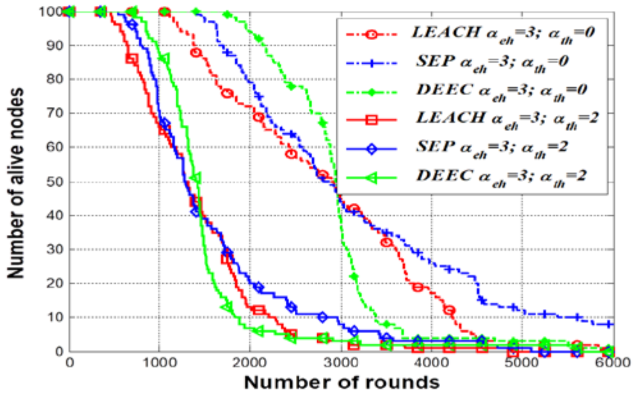

Fig. 2. Effect of traffic heterogeneity on WSN routing algorithms

The performance of proposed algorithm (TEAR) under multi-heterogeneity scenario is depicted in Fig. 3 for ($\alpha_{th} = 4; \alpha_{eh} = 1$), where the stability periods are 285, 280, 291 and 379 for LEACH, SEP, DEEC and TEAR respectively. Fig. 4 shows a similar scenario for ($\alpha_{th} = 2; \alpha_{eh} = 1$), where the stability periods are 521, 448, 567 and 614 for LEACH, SEP, DEEC and TEAR respectively. TEAR shows improvement in the stability period over LEACH, SEP and DEEC algorithms under the multi-heterogeneity scenario. The detailed results of TEAR under different heterogeneity parameter (α_{th} and α_{eh}) are shown in TABLE II, where each instance (mean and standard deviation) is based on analyzing the algorithm on a set of ten random WSN deployments.

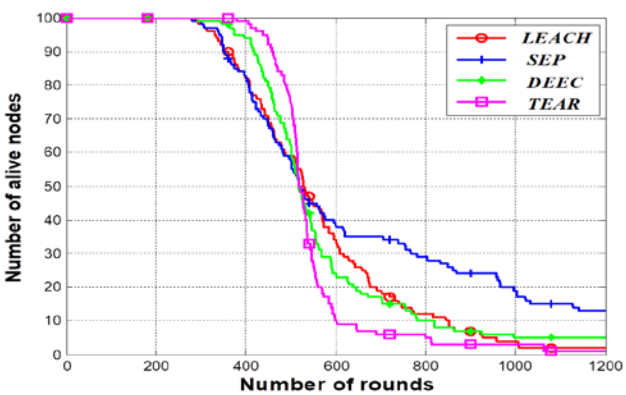

Fig. 3. Stability period in Multi-heterogeneous WSN ($\alpha_{th} = 4; \alpha_{eh} = 1$)

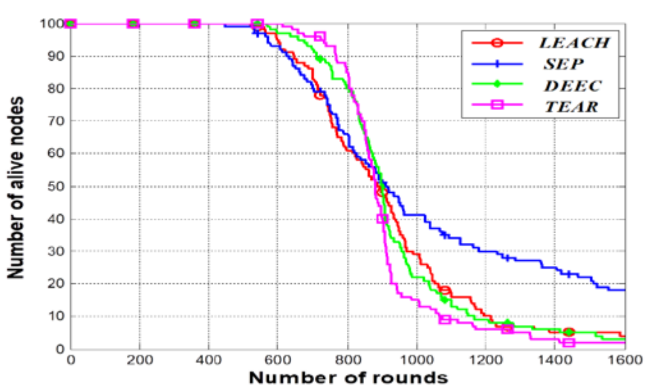

Fig. 4. Stability period in Multi-heterogeneous WSN ($\alpha_{th} = 2; \alpha_{eh} = 1$)

The results show that the extended version of SEP (based on [4]) do not perform well under traffic heterogeneity scenarios. As SEP considers initial energies in CH selection, it does not perform well with increase in traffic loads. DEEC better handles (over SEP) the increase in traffic heterogeneity, as it also considers node's residual energy. TEAR shows improved performance with increased traffic as it additionally considers the traffic loads while making CH decision. In the absence of traffic heterogeneity, TEAR performs like DEEC. However, TEAR performs better than all the three algorithms in the presence of traffic heterogeneity.

TABLE II
STABILITY PERIOD: MEAN (STANDARD DEVIATION)

α_{eh}, α_{th}	LEACH	SEP	DEEC	TEAR
3, 0	1131(56)	1352(63)	1870(99)	1870(99)
2, 2	486(31)	513(51)	658(52)	708(49)
2, 3	376(27)	386(43)	507(34)	538(40)
1, 2	475(27)	450(36)	579(34)	632(29)
1, 3	367(23)	339(18)	438(28)	489(27)
1, 4	295(19)	284(12)	344(31)	392(36)

V. CONCLUSION

Consideration of multi-heterogeneity in WSN routing algorithms can help in achieving optimal resource utilization in realistic scenarios. This letter considers WSN nodes with random levels of energy and traffic heterogeneities. It devises a traffic and energy aware routing (TEAR) technique with an improved CH selection method, which considers node's traffic along with its initial energy and residual energy. TEAR performs better, in terms of stability period, over legacy algorithms (LEACH, SEP and DEEC) in the multi-heterogeneous scenario. Further, the multi-heterogeneity concept (especially the traffic heterogeneity consideration) could be helpful in developing more effective routing algorithms for realistic WSNs and Internet of Things applications with heterogeneous sensing requirements.

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