Delay-Energy Aware Clustering Multi-hop Routing in Wireless Sensor Networks

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Abstract A wireless sensor network (WSN) consist of a large number of low-power sensors that are densely deployed in inhospitable physical environments. Due to limitations of sensors in terms of memory, energy and computational capacities, the most important issue for designing sensor network protocols is energy efficiency. Although energy efficiency is a major concern in WSN, it often suffers from the addition delay. This paper investigates the trade-off between the energy consumption and the end-to-end delay in WSN. We first propose a new distributed clustering approach to determine the best clusterhead for each cluster by considering energy and delay requirements. Next, we provide a multi-hop routing algorithm from clusterheads to sink with a new delay model to calculate the minimum delay-energy cost. Our simulation results are found to be consistent with our theoretical analysis and show the best number of hops to trade-off energy consumption and end-to-end delay.

1 Introduction

Each sensor is equipped with a limited energy resource and difficult to be replaced in the application environment. Therefore, how to design an energy efficient routing protocol becomes the main goal for the WSN. However, in many current applications of WSN such as forest fire detection, data should be transmitted from

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sources to sink within a limited time. If it exceeds this time, data will not be useful anymore. Thus, a trade-off existing between energy consumption and end-to-end delay is extremely necessary.

Although there are many heuristic solutions that have been presented to balance delay and energy consumption in WSN, but their effects is negligible because of long convergence time [1], [2], [3]. Besides, clustering is the technique used very effectively to archive the energy efficiency in WSN [4]. In clustering approach, sensors elect themselves as clusterheads based on the probability values. Because of energy constraints, a sensor in WSN can communicate directly only with other sensors that are within a small distance. To enable communication between sensors not within each other's communication range, the sensors form a multi-hop communication network. In clustering approach, each cluster has a clusterhead that fuse all sensing data from its members and forward it to the sink thereafter. When clusterhead and sink are far from each other, the direct communication between clusterhead and sink makes clusterheads increase energy consumption exponentially with distance [5].

Direct communication provides minimum delay but increases energy consumption. Whereas, multi-hop communication is energy efficient but increases delay [6]. Therefore, in this paper, we present a new methodology called DEM (Delay Energy Multi-hop) for solving the aforesaid problem by considering delay-energy trade-off in multi-hop routing from clusterheads to the sink.

Our major contributions are:

- We have proposed a new delay model to calculate the path cost in multi-hop routing problem.
- We have also presented the new trade-off function and the effect of controlling parameters on energy consumption and end-to-end delay.
- We have found the optimal hop-count value to trade-off energy consumption and end-to-end delay.

The remainder of the paper is organized as follows. In section 2, we discuss existing proposals for this problem and place our work in their context. Section 3 presents network, energy and delay models. Section 4 presents DEM details. Section 5 shows simulation results to confirm the correctness of our theoretical analysis. Finally, section 6 concludes this paper.

2 Related Works

Several works in the literature have attempted to address the problem of energy efficient, delay-constrained routing in WSNs and have met with varying degrees of success.

Clu-DDAS [7], which was proposed by Yingshu Li et al., presents an energy efficient distributed scheduling algorithm based on a cluster-based aggregation tree. By constructing a Cluster-based Data Aggregation Tree, this protocol permits the packet transmissions among different clusters are concurrent and collision-free. However, constructing distributed broadcasting trees generates more overhead.

T.T Huynh et al. proposed a new multi-hop routing scheme to balance energy efficiency and network delay in [8]. Energy*Delay routing algorithm is applied within each cluster while energy-efficient chain construction algorithm is applied for clusterheads to construct energy-efficient chains from clusterheads to the base station. However, it is not flexible for fixed 3-hop clusters as what they proposed.

DEAR (Delay-bounded Adaptive Energy-constrained Routing) [9] is multi-path routing protocol. It is interested in many parameters such as reliability, delay and energy consumption. This protocol allows packets are continuously distributed across the network even if the paths are going to crash. It balances the delay between the different paths by providing a polynomial-time algorithm for solving the multi-objective optimization problem. However, energy and network delay efficiency is limited for the complexity of the algorithm.

In [10], authors have analyzed trade-off between delay and energy for data aggregation. They have shown that WSN suffers from energy consumption with non-aggregation methods and it suffers from delay when full aggregation method is used. In [11], authors have proposed Delay-Energy Aware routing Protocol (DEAP) for heterogeneous sensor and actor networks. Energy saving is achieved by using resources of actor nodes whenever possible. It not only uses adaptive energy management scheme to control wakeup cycle of the sensor nodes based on the delay experienced by the packets, but also uses geographical information for load balancing to achieve energy consumption.

In [12], authors have analyzed energy delay trade-off during the deployment of WSN. They have proposed a formal model that can be used to compare the performance of the different protocols and algorithms. In [13], authors have divided energy efficient routing into two subproblems. First problem is how to construct efficient routing trees. Second problem is how to assign wakeup frequency assignment with multiple routing trees. Authors have provided a solution to the first problem by an optimal algorithm and they have proven the second problem as NP-hard and provided polynomial time approximation algorithm.

In [6], authors have proposed data forwarding protocols for Trade-off Energy with Delay (TED) by slicing communication range of sensors into concentric circles. In[14], authors have proposed energy delay trade-off for intra-cluster routing in WSN.

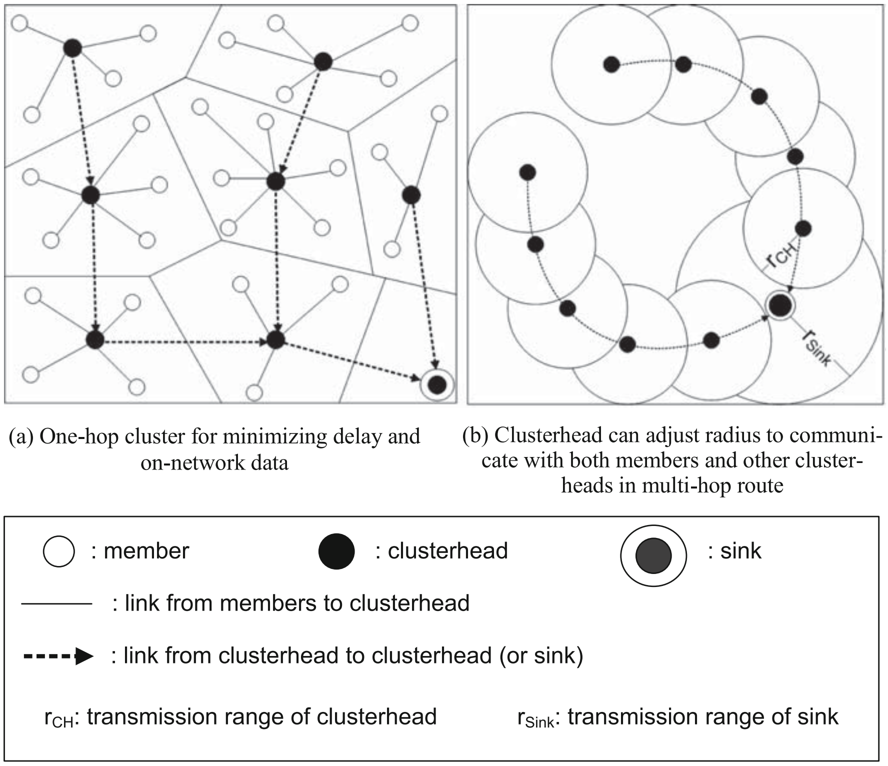
Akkaya and Younis [15] propose a routing protocol that finds an energy-efficient path along which the end-to-end delay requirements of a connection are met. They assume that the sensor nodes have a class-based, priority queueing mechanism and through this, convert the delay requirements into bandwidth requirements. Their approach, however, does not take into consideration the delay factors that can occur due to channel contention at the MAC layer.

3 Network, Energy and Delay Model

3.1 Network Model

Consider a set of sensors dispersed in a field, we employ the hierarchical network model shown in figure 1 with assumptions as follow:

- All sensors are stationary, have similar capabilities and equal significance.
- All sensors can be aware of their own residual energy and adapt transmission power according to communication distances.
- Links are symmetric and the radio signal has identical energy attenuation in all directions.
- Data exchanged between two communicating sensors, not within each others' radio range, is forwarded by other sensors.
- All sensors are capable of operating in clusterhead mode and sensing mode.
- Data fusion is used to reduce the total data sent. Each sensor transmits data at given time slot. The data sensed by adjacent nodes are correlative, so the clusterhead can fuse the collective data.



(a) One-hop cluster for minimizing delay and on-network data

(b) Clusterhead can adjust radius to communicate with both members and other clusterheads in multi-hop route

Fig. 1 Hierarchical wireless sensor network model

3.2 Delay Model

An end-to-end delay, denoted by $D_{ete}(x, s)$, is the time elapsed between the departure of a collected data packet from a source x and its arrival to a sink s.

The end-to-end delay can be calculated using rules related to the queue theory. The queues in the nodes are considered to be of type M/M/1. In these types of queues, the input is of type Poisson, the output is an exponential random variable and the number of servicers is 1. Queuing delay d_Q in these queues is calculated by following equation:

$$d_Q = \frac{1}{\mu-\lambda} \tag{1}$$

where μ is the service rate which is an exponential stochastic variable and λ is the rate of entry for new packets which is a Poisson stochastic variable.

By definition, an end-to-end delay $D_{ete}(x,s)$ includes the average values of queuing delay d_Q per intermediate data disseminator (clusterhead), transmission delay d_T, and propagation delay d_P. In other words:

$$D_{ete}(x,s) = \left(d_Q + d_T + d_P\right) \times k_{(x,s)} \tag{2}$$

where d_Q is caculated by equation (1); $d_T = \frac{l}{\psi}$; $d_P = \frac{d}{\gamma}$; $k_{(x,s)}$ is the total number of data forwarders (cluserheads) between a source x and the sink s.

Then, equation (2) can be rewritten as follow:

$$D_{ete}(x,s) = \left(\left(\frac{1}{\mu-\lambda}\right) + \frac{l}{\psi} + \frac{d}{\gamma}\right) \times k_{(x,s)} \tag{3}$$

where l is the packet size (bits), ψ is the link bandwidth (bps), d is the length of physical link and γ is the propagation speed in medium (m/sec).

4 DEM Details

DEM is a distributed clustering scheme which operates in rounds, and each round is separated into two phases: network organization and data transmission. The former stage's task is to establish cluster network's topology and build multi-hop routing; the latter stage is to transmit data from clusterheads to sink via multi-hop forwarding.

4.1 Network Organization

Cluster Setup

Algorithm begins with neighbor discovery phase which is initiated by the sink by broadcasting an ADV message to all nodes at a certain power level, and each node compute its approximate distance d_{toSink} according to the received signal strength.

Each node waits for $\tau = \frac{1}{E}$ time before broadcasting an ADV(ID,E) message to its neighbors and collects the correlative data of the neighbors, where *ID* is node identifier and *E* is residual energy. Each node compares its energy level with the energy level of the nodes from which it has received ADV messages. If the node has less energy than others. it will cancel its timer and decides to be a cluster member (non-clusterhead).

The probable clusterheads are the set of nodes, which have sent ADV messages and after that either they do not receive any ADV messages or their energy is higher than the energy received in ADV messages. It may be possible that more than one node may have the same energy level and they are in communication range of each other. To break a tie in such cases, Trade-off for Energy and Delay (TED) is used. TED is calculated for sensor *i* from equation (4) only for the probable clusterheads. Values of α and β lie in the range of [0,1] and $\alpha+\beta \neq 0$.

$$TED_i = \left(\frac{E_i}{E_{total}}\right)^{\alpha} + \left(\frac{1}{d_{(i,s)}}\right)^{\beta} \tag{4}$$

Each probable clusterhead *i* will wait for $\omega = \frac{1}{TED_i}$ time before doing announcement that it is a final clusterhead. All probable clusterheads, which receive final clusterhead announcement cancel their TED timers to become the member nodes for the current round. After the procedure of cluster formation has finished, all clusterheads broadcast TDMA message to allocate time slot for their cluster members.

Inter-cluster Multi-hop Routing Algorithm

Calculating initial path cost

Each clusterhead estimates the transmission distance d_{toSink} using the beacon message broadcasted by sink and calculates the energy consumption of sending data to the sink in one hop. This value will be set as the initial path cost, and broadcasted along with ADV as an information field during cluster setup phase. The initial path cost is calculated by equation (5):

$$cost_0(CH_i) = E_{TX}^{i}(l, d_{toSink}) + D_{ete}(i, s) \tag{5}$$

where $E_{TX}^{i}(l, d_{toSink})$ is energy spent for transmission of a *l*-bit data from clusterhead *i* to the sink over distance d_{toSink}, given by equation (6); and $D_{ete}(i, s)$ is the end-to-end delay between the departure of the data packet from the clusterhead *i* and its arrival to the sink *s*, given by equation (7) that is derived from (3):

$$E_{TX}^{i}(l, d_{toSink}) = \begin{cases} l \times E_{elec} + l \times \varepsilon_{fs} \times d_{toSink}^{2} & if\ d_{toSink} < d_0 \\ l \times E_{elec} + l \times \varepsilon_{mp} \times d_{toSink}^{4} & if\ d_{toSink} \geq d_0 \end{cases} \tag{6}$$

$$D_{ete}(i, s) = \left(\left(\frac{1}{\mu - \lambda}\right) + \frac{l}{\psi} + \frac{d}{\gamma}\right) \times k_{(i,s)} \tag{7}$$

Updating path cost

After receiving the ADVs from other clusterheads, each clusterhead estimates the distance to other clusterheads, and calculates the forwarding path cost when other clusterheads act as forwarding nodes. If the cost is less than the initial value, it will be regarded as the updated path cost value. Each clusterhead may have several forwarding paths with smaller cost than the initial value; it selects the path with the minimum cost as default forwarding path, and declares the new path cost in ADV broadcasting.

Through iteration, each clusterhead can set up an optimum multi-hop routing. The routing table built by such method only contains one forwarding clusterhead and all the reachable routes when itself acts as a forwarding node. The suboptimal forwarding clusterheads and the corresponding path cost are saved in standby routing table. During the transmission period, if the optimal forwarding path is failed, the suboptimal one is selected as a substitution.

Path cost of clusterhead *i* using clusterhead *j* as forwarding node is given by the following iterative equation:

$$cost(CH_i) = E_{TX}^{i}(l, d_{ij}) + D_{ete}(i, j) + cost_F(CH_j) \tag{8}$$

$$cost_F(CH_j) = E_{RX}^{j}(l, d_{ij}) + cost(CH_j) \tag{9}$$

where d_{ij} is the distance between any two adjacent clusterheads i and j; $E_{TX}^{i}(l, d_{ij})$ is the energy consumption of clusterhead i when it sends l-bits message to clusterhead j; $E_{RX}^{i}(l, d_{ij})$ is the energy consumption of clusterhead j when it receives l-bits message from clusterhead i; $cost_F(CH_j)$ is the forwarding path cost of clusterhead j. Particularly, if clusterhead j is the last forwarding node, $cost(CH_j) = cost_0(CH_j)$.

4.2 Data Transmission

Once the inter-cluster multi-hop routing is created, data transmission begins. Each member turns off the radio until its allocated transmission time, and then sends the sensing data to the clusterhead during its time. The clusterhead keeps its receiver on to receive the data from the nodes in the cluster. After all the data has been received, the clusterhead aggregates data packets into a single packet to reduce redundancy and transmission energy, and then sends data to the other clusterhead which forwards the received packet toward the sink. After a certain time, the next round begins with setup phase again.

During data collection, the energy consumption of each node is as follows. The member only needs to send the sensing data to the clusterhead, so its energy consumption is:

$$E_{mem}(j) = l \times E_{elec} + l \times \varepsilon_{fs} \times d(j)^2 \tag{10}$$

The clusterhead needs to fuse the all intra-cluster data and forwards the inter-cluster data from the other clusterheads, so its energy consumption is:

$$E_{CH}(i) = E_R(i) + E_F(i) + E_S(i) \tag{11}$$

$$E_R(i) = l \times E_{elec} \times \left(size_{CH}(i) + relays(i)\right)$$

$$E_F(i) = size_{CH}(i) \times E_{fuse} \times l$$

where $E_R(i)$is the energy spent to receive all intra-cluster data, $E_F(i)$is the energy spent to fuse all intra-cluster data, $E_S(i)$ is the energy spent to transmit *l*-bit data to other clusterhead or sink (same as equation (6)), $size_{CH}(i)$ denotes the number of member nodes which belong to the clusterhead i, *relays(i)* is the times of relay, $d_{next}(i)$ is the distance from clusterhead *i* to its next hop.

Then, the total energy consumption for each round is:

$$E_{total} = \sum_{i=1}^{K} E_{CH}(i) + \sum_{j=1}^{N-K} E_{mem}(j) \tag{12}$$

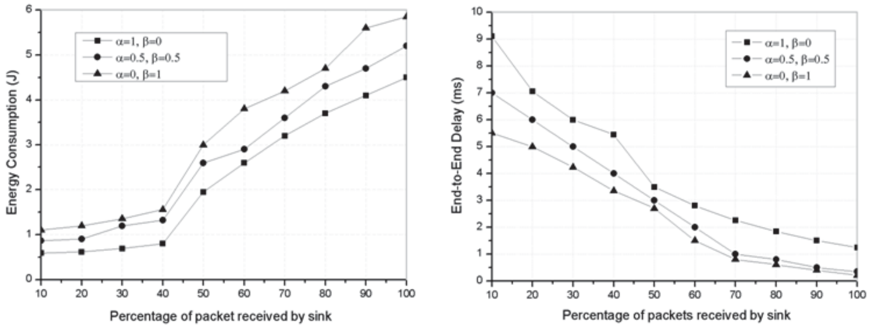
where *K* is the number of clusterheads, *N* is the number of sensors in the network.

5 Simulation Results

We simulate a clustered wireless sensor network for 100 nodes in a field with dimensions 100m×100m using MATLAB 8.1. Sink is located at (50,50), the data message size is 30 bytes, $\lambda = 3$, $\mu = 6$, initial energy of node is 1 Joule, Eelec = 50nJ/bit, ε_{fs} = 10pJ/bit/m^2, ε_{mp} = 0.0013pJ/bit/m^4, $E_{fuse} = E_{fuse}$, ψ = 40bps, γ = 50m/s.

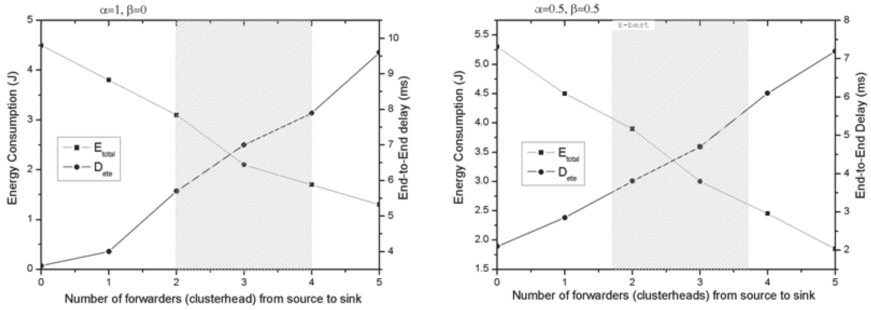
To see the effect of α and β on DEM, we set values of α and β to 0 and 1 respectively and measures end to end delay and energy consumption. When $\alpha = 0$ and $\beta = 1$, then variation in the values of TED in equation (4) is due to the β. Hence, it indicates that end-to-end delay is more important for a given application. On the other hand, when $\alpha = 1$and $\beta = 0$, then variation in the values of TED is due to the α, which indicates that energy consumption is more important for the given application compared to end-to-end delay. In figure 2(a), we plot the expected total energy consumption associated with percentage of packets received by sink. As can be seen, the energy spent in data dissemination decreases as α increases respectively. In figure 2(b), we plot the expected end-to-end delay associated with percentage of packets received by sink. As can be seen, the end-to-end delay decreases as $d_{(i,s)}$ increases given that the delay is inversely proportional to $d_{(i,s)}$. Indeed, as the distance between any pair of consecutive forwarders increases, the number of times a data packet will be forwarded decreases and hence the end-to-end delay decreases.

In order to gain more insight regarding the behavior of energy consumption and delay metrics with respect to the number of data forwarders, we consider the following plots where both E_{total} (equation 12) and $D_{ete}(x,s)$ (equation 7) are plot on the same figure. Figure 3 shows how energy consumption and delay vary depending on the number of data forwarders, which helps WSN application designers get an idea about the values of $k_{(i,s)}$ that could be used to trade-off energy consumption with end-to-end delay. In figure 3(a), for $\alpha = 1$ and $\beta = 0$, a source could use the $k = 3$ (4 hops) as a good candidate to minimize both metrics. In figures 3(b) and 4(c), for ($\alpha = 0.5$ and $\beta = 0.5$) or ($\alpha = 0$ and $\beta = 1$), either $k = 2$ or $k = 3$ is a good choice.

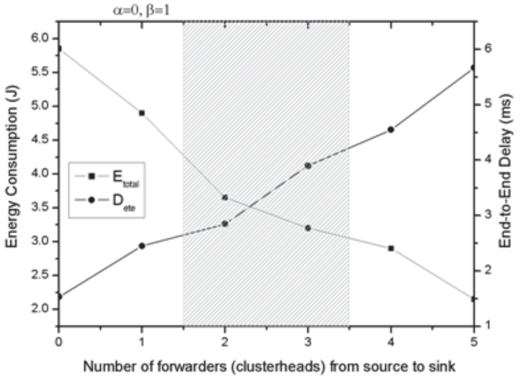


(a) Effect on Energy consumption (b) Effect on the end-to-end delay

Fig. 2 Effect of α and β on energy consumption and end-to-end delay



(a) Trade-off for $\alpha = 1$ and $\beta = 0$ (b) Trade-off for $\alpha = 0.5$ and $\beta = 0.5$



(c) Trade-off for $\alpha = 0$ and $\beta = 1$

Fig. 3 Trade-off between Energy consumption and End-to-End delay

6 Conclusions

In this research, we have proposed a new distributed clustering approach to determine the best clusterhead for each cluster in WSNs in order to trade-off energy consumption and end-to-end delay. The regular nodes join clusters where clusterheads elected by TED value regarding both of energy and delay. We have also proposed a cost function for the inter-cluster multi-hop routing algorithm based on the new delay model. By simulation, we have found the optimal parameter values to trade-off energy concumption and end-to-end delay.

References

1. Zhang, X., Zhang, L.: Optimizing energy-latency trade-off in wireless sensor networks with mobile element. In: IEEE 16th International Conference on Parallel and Distributed Systems (2010)
2. Jin, Y., Wei, D.: Latency and energy - consumption optimized task allocation in wireless sensor networks. In: IEEE Wireless Comm and Networking Conference (2010)
3. Allirani, A., Suganthi, M.: An energy sorting protocol with reduced energy and latency for wireless sensor networks. In: IEEE Inter. Conf. on Advance Computing (2009)
4. Boyinbode, O., et al.: A survey on clustering algorithms for wireless sensor networks. In: IEEE 13th International Conference on Network-Based Information Systems (2010)
5. Heinzelman, W.B., et al.: An application specific protocol architecture for wireless sensor network. IEEE Transactions on Wireless Communications **4**, 660–670 (2002)
6. Ammari, H.M.: On the energy-delay trade-off in geographic forwarding in always-on wireless sensor networks: A multi-objective optimization problem. Comput. Netw. **57**(9), 1913–1935 (2013)
7. Li, Y., et al.: An energy efficient distributed algorithm for minimum latency aggregation scheduling in wireless sensor networks. In: IEEE 30th International Conference on Distributed Computing Systems (2010)
8. Huynh, T.T., Hong, C.S.: An Energy*Delay Efficient Multi-Hop Routing Scheme for Wireless Sensor Networks. IEICE Transactions on Information and Systems **E89-D**(5), 1654–1661 (2006)
9. Bai, S., et al.: DEAR: delay-bounded energy-constrained adaptive routing in wireless sensor networks. In: IEEE International Conference on Computer Communications (2012)
10. Wuyungerile, L., et al.: Tradeoff between delay and energy consumption of partial data aggregation in wireless sensor networks. In: The Fifth International Conference on Mobile Computing and Ubiquitous Networking (2010)
11. Durresi, A., et al.: Delay-energy aware routing protocol for sensor and actor networks. In: The 11th Int. Conf. Parallel Distrib. Syst., pp. 292–298 (2005)
12. Moscibroda, T., et al.: Analyzing the energy-latency trade-off during the deployment of sensor networks. In: Proc. 25th INFOCOM, pp. 1–13 (2006)
13. Cohen, R., Kapchits, B.: Energy-delay optimization in an asynchronous sensor network with multiple gateways. In: Proc. 8th Annu. IEEE SECON, pp. 98–106 (2011)
14. Shahraki, A., et al.: A new approach for energy and delay trade-off intra-clustering routing in WSNs. Comput. Math. Appl. **62**(4), 1670–1676 (2011)
15. Akkaya, K., Younis, M.: Energy-aware routing of time-constrained traffic in wireless sensor networks. Journal of Communication Systems, Special Issue on Service Differentiation and QoS in Ad Hoc Networks **17**(6), 663–687 (2004)