Delay Analysis of Large-Scale Wireless Sensor Networks

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Abstract. For wireless sensor network applications, the latency from the sensing of the event to the reporting through the network is critical. In this paper, we try to characterize the delay incurred by sensed packets traversing across the network. We derive the source and destination distance, hop count distribution under typical sensor traffic patterns. Then how various network parameters, such as the node density and the transmission range, impact on delay and delay distribution is investigated. The results of our research can provide insights in designing both flat and cluster-based sensor networks to meet the specified delay requirement.

Keywords: wireless sensor networks, clustering, delay, diameter, hop count, Voronoi diagram.

1 Introduction

Recent technical advances have enabled the large-scale deployment and applications of wireless sensor nodes. These small in size, low cost, low power sensor nodes is capable of forming a network without underlying infrastructure support. Such a wireless network is called a wireless sensor network (WSN). It consists of spatially distributed autonomous sensor nodes to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations[1,2,3]. Sensor nodes consist of sensing, data processing and communication components. Their functions are to sense data from the environment, process the data, and finally transmit the data to the destination. Because of sensor nodes' reliability, accuracy, cost effectiveness, and easy deployment, WSN is emerging as a key tool for various applications including home automation, traffic control, search and rescue, and disaster relief.

In general wireless ad hoc networks, we are concern with the throughput and spatial re-use. Sensor networks make less demand on the throughput performance; rather delay is an important quality of service (QoS) parameter for sensor networks [4]. In lots of sensor network applications, sensed data needs to be transmitted and forwarded to the sink node in a timely manner. A sink node acts like a gateway between the sensor network and the exterior network.

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Due to the large network size, packets need to traverse large number of intermediate nodes to reach destination, or the sink node. Furthermore, most sensor networks adopt power management schemes[5,6,7], where nodes are powered on and off periodically. These schemes save energy at the cost of extra delay for each hop, and the end-to-end delay incurred by sensed packets becomes much larger consequently. It is important to characterize the delay for the delivery of sensed packets and to determine how the parameters, such as network size, transmission range and node density, affect the delay performance.

Different from existing works focusing on a new MAC or routing protocol design to reduce delay and energy consumption, we study the delay properties of large scale sensor networks in an analytical framework. Without loss of generality, we assume an uncoordinated sensor MAC protocol in our work. By obtaining distance distribution between source and destination nodes in sensor networks under typical traffic patterns, we characterize the delay incurred by sensed packets. Furthermore, we extend our analysis to a two-tier architecture where there are two types of sensor nodes. The more powerful nodes function as clusterheads [8], and traffic is aggregated within the cluster to the clusterhead. We determine how the introduction of the clustering architecture impacts on the delay performance. Our work has application in choosing network parameters, such as node density, transmission range, and the number of clusterheads to meet the delay requirements.

The paper is organized as follows. In the next section, related works are discussed. In section III, we characterize the distance distribution between source and destination pairs for typical traffic patterns in the sensor networks: (1) random source to random destination and (2) multiple source to a single central sink node traffic. Delay properties are then derived based on the distance distribution. We also extend the analysis to the two-tier structure, where the more powerful nodes are deployed as clusterheads. The last part is the conclusion.

2 Related Work

Several sensor MAC protocols, most notably STEM [5] and SMAC [6], have been proposed for use in sensor network. These schemes trade the delay of each hop with the energy saving. Specifically, the tradeoff between the energy saving and the delay has been identified by Schurgers et al. [5]. Yu et al. [9] analyzed the tradeoff between the latency and the energy consumption from the perspective of data aggregation. Lu et al. [10] tries to improve the end-to-end delay by assigning the time slots to sensor nodes optimally. Dousse et al. [11] study the delay using blinking Poisson boolean model. Gamal et al. [12] shows the tradeoff between the delay and the energy efficiency in the physical layer. The most relevant work was done by Zorzi et al. [13], and they study the multi-hop performance by analyzing the hop count in a geographic random forwarding routing scheme.

To the best of our knowledge, delay analysis for typical traffic patterns in the sensor networks has not been treated in the literature. In this paper, we base our analysis on a general assumption of an uncoordinated sensor MAC protocol, where synchronization is not pre-assumed. It should be noted that for this MAC protocol, the delay of each hop is a random variable. Our analysis can also be extended for special cases where each hop delay is fixed.

3 Delay Analysis

In the large-scale sensor networks, the hop count the packet needs to traverse in the network to reach the destination and the delay of each hop in the MAC layer determine the overall end-to-end delay. Compared with the delay introduced by energy management scheme in typical sensor MAC protocols [5][6], the queueing delay and the packet processing delay can be neglected.

In this section, we analyze the S/D distance distribution under typical traffic pattern in the sensor network, and try to characterize the delay based on the results in the last section.

3.1 Delay of Each Hop

General sensor networks are mostly based on uncoordinated MAC protocols since it is expensive to achieve synchronization [14]. Under completely uncoordinated MAC such as STEM[5], the delay of each hop d is a random variable between 0 and T_s, where T_s is the sleeping/wakeup interval. $\mathsf{E}(d)$ denotes the average delay of each hop and $\mathcal{V}(d)$ is the variance of the delay of each hop. Thus,

$$\mathsf{E}(d) = \frac{T_s}{2}, \tag{1}$$

and,

$$\mathcal{V}(d) = \int_0^{T_s} [s - \mathsf{E}(d)]^2 \frac{1}{T_s} ds = \frac{{T_s}^2}{12}. \tag{2}$$

The delay of each hop can be seen as an independent and identical random variables with mean $\frac{T_s}{2}$ if the MAC is completely uncoordinated. The end-to-end delay S_h between two nodes being h hops away, can be expressed as sum of independent and identically distributed random variables. If h is large, the probabilistic distribution of S_h can be approximated by central limit theorem [15]:

$$\begin{aligned} \mathsf{P}[S_h] &= \frac{1}{\sqrt{2\pi}\mathcal{V}(d)} e^{-\frac{[S_h - \mathsf{E}(d)]^2}{2\mathcal{V}(d)^2}}, \\ \mathsf{E}[S_h] &= h\mathsf{E}\left(d\right), \ and \\ \mathcal{V}[S_n] &= h\mathcal{V}(d). \end{aligned} \tag{3}$$

3.2 Delay between Random Source and Destination

In general sensor network applications, sensor nodes perform sensing and the sensed packets are forwarded to sink node in a multi-hop manner. On the other hand, in complex sensor networks performing in-network query or aggregation, there might exist traffic between random pairs of traffic source and destinations. This type of traffic is treated in this section and the former case will be discussed in the next section.

The distribution of the distance between random source and destination pairs was first investigated in [16]. It is further shown in [17] that the PDF can be closely approximated via Gaussian distribution with mean $\frac{L}{2}$ and standard derivation $\frac{L}{3.5}$, when nodes are randomly deployed in a square area of $L \times L$. Here we adopt the PDF introduced in [18]. For a rectangle area of size $a \times b$, the PDF of the distance between random S/D, denoted by $\mathsf{P}_{S/D}[\gamma]$, is as follows[18]:

$$\mathsf{P}_{S/D}[\gamma] = \frac{4\gamma}{a^2 b^2}\left(\frac{\pi}{2}ab - a\gamma - b\gamma + \frac{1}{2}\gamma^2\right). \quad (4)$$

For our deployed square area, $a = b = L$. For distance γ, the required hop count can be approximated via $\lceil \frac{\gamma}{F(\theta, r_0, \lambda)} \rceil$, where function F is F_{topo} for energy efficient routing with power control case or F_{2D} for shortest path routing with power control [19].

The hop count between random S/D pairs is a random variable, denoted by H.

$$\begin{aligned} \mathsf{P}[H = h] &= \mathsf{P}_{S/D}\left[\frac{\gamma}{F(\theta, r_0, \lambda)} = h\right] \\ &= F(\theta, r_0, \lambda)\mathsf{P}_{S/D}\Big[hF(\theta, r_0, \lambda)\Big]. \end{aligned} \quad (5)$$

Assuming that packets incur the same fixed delay at each hop, we can then drive the PDF of the delay incurred for all the random S/D traffic in the network from Equ. (5). For uncoordinated MAC with random delay of each hop, we can obtain the average delay.

The average delay incurred by all the random S/D pairs, denoted by $\mathsf{E}\,(Delay)$ can be expressed as:

$$\begin{aligned} \mathsf{E}\,(Delay) &= \mathsf{E}\Big[\mathsf{E}(d \mid hopcount = h)\Big] = \mathsf{E}\left(h\frac{T_s}{2}\right) \\ &= \frac{T_s}{2F(\theta, r_0, \lambda)} \int_0^{\sqrt{2}L} \mathsf{P}[\gamma]\gamma d\gamma \\ &= \frac{2\sqrt{2}L(\frac{2}{3}\pi - \frac{8}{5})}{F(\theta, r_0, \lambda)}. \end{aligned} \quad (6)$$

In some circumstances, we do care about the maximum delay. The diameter is defined as the maximum hop count in all the shortest paths between all the node pairs in a network [20]. If the diameter of the networks is D, the maximum delay a sensed packet might suffer can be expressed as:

$$MaxDelay = DT_s. \quad (7)$$

For the random deployment in an $L \times L$ square area, the diameter can be approximated by:

$$D = \frac{\sqrt{2}L}{F(\theta, r_0, \lambda)}. \quad (8)$$

We perform simulation in a graph simulator implemented in C++. 500 nodes randomly deployed in a area of 1000×1000. Floyd algorithm [21] is used to compute the shortest path between any pair of nodes in the network. Fig. 1 shows the average hop count between random source and random destination over 50 randomly generated topologies.

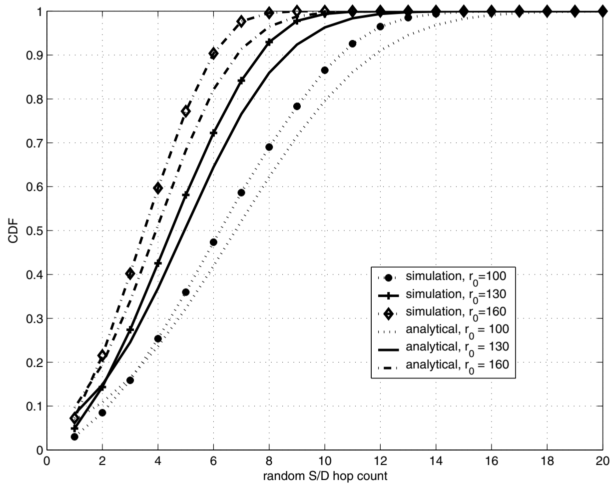

Fig. 1. Hop count distribution between random pairs

3.3 Delay from Multiple Sources to One Sink

In this part, we look into the case where a sink node is located at the center of the deployed area and sensor nodes send sensed packets to the sink node via multi-hop forwarding. We first consider a flat sensor network organization, and then perform the analysis for a two-tier architecture.

Flat architecture. To facilitate our analysis, we suppose that the nodes are deployed in a circle area with radius R, and the node density is λ. The distance from a node to the central sink node is a random variable, denoted by υ_1.

$$\mathsf{P}[\upsilon_1 \le \xi] = \frac{\xi^2}{R^2}. \quad (9)$$

And,

$$\mathsf{P}[\upsilon_1 = \xi] = \frac{2\xi}{R^2}. \quad (10)$$

The PDF of hop count in the flat architecture can be derived using Equ. (5), where $P_{S/D}$ should be replaced by Equ. (10).

The average distance to the sink node $\mathsf{E}(\upsilon_1)$ can be expressed as:

$$\mathsf{E}(\upsilon_1) = \int_0^R \frac{2\xi^2}{R^2} d\xi = \frac{2R}{3}. \tag{11}$$

The average delay can be derived as:

$$\begin{aligned}\mathsf{E}\left(Delay\right) &= \mathsf{E}\big[\mathsf{E}(d \mid hopcount = h)\big] \\ &= \frac{T_s}{2} \int_0^R \mathsf{P}[\upsilon_1] \frac{\upsilon_1}{F(\theta, r_0, \lambda)} d\upsilon_1 \\ &= \frac{T_s R}{3F(\theta, r_0, \lambda)}. \end{aligned} \tag{12}$$

Two-tier architecture with two types of sensor nodes. In the flat architecture, sensed packets, need to be forwarded to the sink node via intermediate nodes. For large sensor networks, the delay and the energy consumption in flat architecture is unbearable. To improve the scalability of sensor networks, hierarchical architecture has to be introduced [22,23]. Suppose there are two kinds of nodes, $K1$ and $K2$. Nodes $K1$ are more powerful than nodes $K2$. We consider a two tier sensor structure, where $K1$ and $K2$ type sensors act as clusterheads(CHs) and normal sensor nodes respectively. Sensor nodes $K2$ always choose the nearest $K1$ nodes as their clusterhead, as shown in Fig. 2. We assume that the $K1$ nodes have enough power conserve and are connected to each other through high bandwidth links and the delay incurred by data transmissions between CHs can be negligible. The density of nodes $K1$ and $K2$ are λ_1 and λ_2 respectively.

Regular clusterhead placement
We first consider a regular $K1$ CH placement where the node deployment area is partitioned into hexagonal areas and CH is located at the center of the hexagon. $K2$ nodes are randomly deployed. Suppose the radius of a cell is Z. The hexagonal area covered by one cell is $\frac{3\sqrt{3}Z^2}{2}$ (shown as Fig. 3). Thus, for a deployment area $L \times L$, the number of cells N can be approximated as:

$$N \approx \frac{L \times L}{\frac{3\sqrt{3}Z^2}{2}}. \tag{13}$$

We define the random variable of the distance from a node to its CH in the two tier architecture as υ_2. The average distance for a single cell has been derived as Equ. (11):

$$\mathsf{E}(\upsilon_2) = \frac{2Z}{3} \approx \sqrt{\frac{8L^2}{27\sqrt{3}N}} = \sqrt{\frac{8}{27\sqrt{3}\lambda_1}}, \tag{14}$$

where λ_1 is the node density of $K1$ nodes.

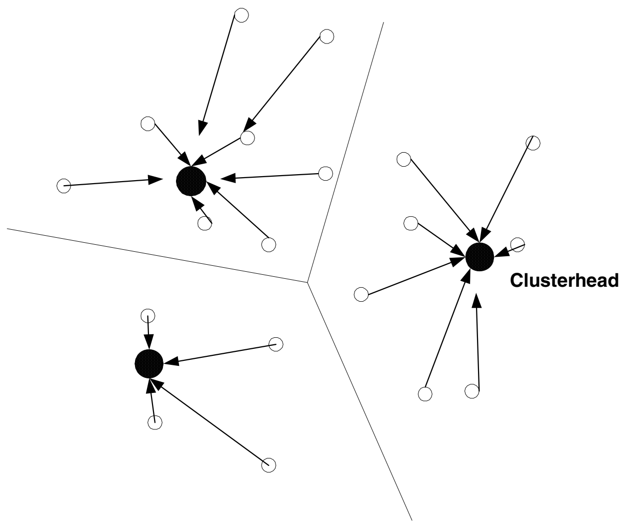

Fig. 2. Two tier clustering based on Voronoi diagram

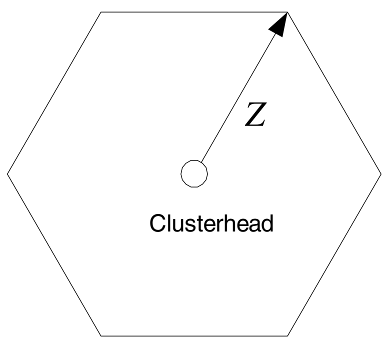

Fig. 3. Hexagon cell in regular deployment

Probabilistic analysis
When both $K1$ and $K2$ nodes are randomly deployed, Voronoi diagram [24,3] can be used to cluster the $K2$ sensor nodes into different Voronoi cells, where a $K2$ sensor node chooses its nearest $K1$ sensor node as its CH. Sensed data from $K2$ nodes are transmitted to their CH via multi-hop forwarding. Denote the distance from a $K2$ node to its CH by υ_2. The probability of $\mathsf{P}[\upsilon_2 \leq \xi]$ can be expressed as:

$$\begin{aligned} \mathsf{P}[\upsilon_2 \leq \xi] &= 1 - \mathsf{P}[\upsilon_2 > \xi] \\ &= 1 - e^{-\lambda_1 \pi \xi^2}. \end{aligned} \tag{15}$$

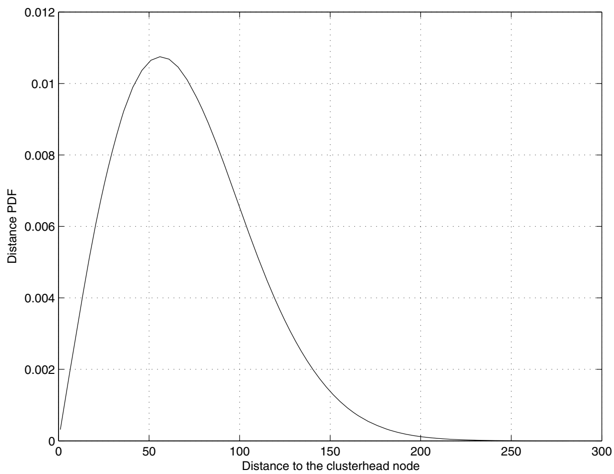

Fig. 4. Distance distribution of different distance from the clusterhead

Thus,

$$\mathsf{P}(\upsilon_2 = \xi) = 2\pi\lambda_1 \xi e^{-\lambda_1 \pi \xi^2}. \tag{16}$$

Fig. 4 shows the probability density function of distance in the two tier sensor networks, where the number of $K1$ nodes is set to 50, and the number of $K2$ nodes is set to 300. The transmission range of $K2$ nodes, denoted by r_0, is set to 80.

The average of υ_2, denoted by $\mathsf{E}(\upsilon_2)$, can be expressed as:

$$\mathsf{E}(\upsilon_2) = \int_0^R 2\pi\lambda_1 \xi^2 e^{-\lambda_1 \pi \xi^2} d\xi. \tag{17}$$

When $R \to \infty$, $E(\upsilon_2)$ can be derived as Equ. (18) [25].

$$\mathsf{E}(\upsilon_2) = \frac{2}{\sqrt{\lambda_1}}. \tag{18}$$

From Equ. (18), we can see that for a large two tier sensor network, the average distance decrease on the order of ${\lambda_1}^{-\frac{1}{2}}$. This result is consistent with Equ. (14) derived for regular $K1$ nodes deployment.

$$\begin{aligned} \mathsf{E}\left(Delay\right) &= \mathsf{E}\Big[\mathsf{E}(d \mid hopcount = h)\Big] \\ &= \frac{T_s}{2}\int_0^{2\sqrt{L}} \mathsf{P}[\upsilon_2]\left\lceil \frac{\upsilon_2}{F(\theta, r_0, \lambda)} \right\rceil d\upsilon_2 \\ &= \frac{T_s}{F(\theta, r_0, \lambda)\sqrt{\lambda_1}}. \end{aligned} \tag{19}$$

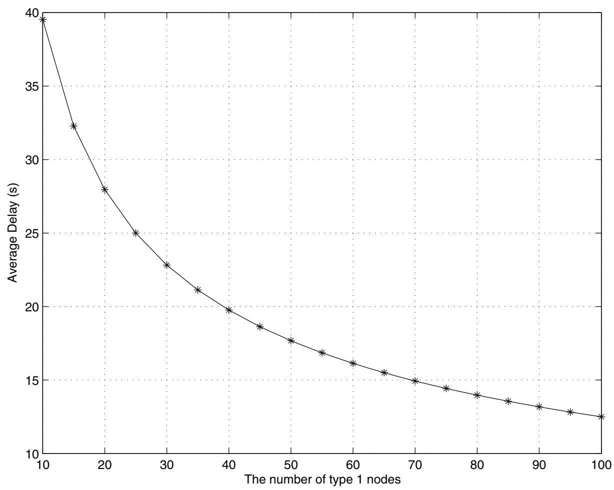

Fig. 5. Average delay variation with the deployment of more $K1$ nodes

Fig. 5 shows the numeric results on the average delay in a network where the number of type $K2$ nodes is 300, and the number of CH nodes ($K1$) increases from 10 to 100. r_0 is 80 and the sleeping interval T_s is 10 seconds.

4 Conclusion

In this paper, we have presented the analysis for the delay properties in the large-scale sensor networks. We quantified both the relationship between the transmission range and delay of each hop, and the delay properties. The S/D distance distributions under typical sensor traffic patterns are derived. Furthermore, the delay is analyzed for the two-tier architecture; how the introduction of more powerful nodes as CHs can improve the delay performance is investigated. Our work can provide guidelines in choosing network parameters to meet the delay requirements.

In our work, we have assumed a deterministic link model and the dynamics of wireless link [26] is not considered. And our delay analysis does not consider the circumstances where an incrementally constructed data aggregation tree [20] is used to deliver the sensed packet. The investigation into this topic will be our future work.

References

1. Estrin, D., Govindan, R., Heidemann, J., Kumar, S.: Next century challenges: scalable coordination in sensor networks. In: MobiCom 1999: Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking, pp. 263–270. ACM Press, New York (1999)

2. Agrawal, D.P., Zeng, Q.-A.: Introduction to Wireless and Mobile Systems. Brooks/Cole Publishing (2003)
3. Ghosh, A., Das, S.K.: Review: Coverage and connectivity issues in wireless sensor networks: A survey. Pervasive Mob. Comput. 4(3), 303–334 (2008)
4. Dousse, O., Tavoularis, C., Thiran, P.: Delay of intrusion detection in wireless sensor networks. In: MobiHoc 2006: Proceedings of the 7th ACM international symposium on Mobile ad hoc networking and computing, pp. 155–165. ACM, New York (2006)
5. Schurgers, C., Tsiatsis, V., Ganeriwal, S., Srivastava, M.: Topology management for sensor networks: exploiting latency and density. In: Proceedings of the 3rd ACM international symposium on Mobile ad hoc networking & computing, pp. 135–145. ACM Press, New York (2002)
6. Ye, W., Heidemann, J., Estrin, D.: An energy-efficient MAC protocol for wireless sensor networks. In: Proceedings of IEEE Infocom 2002, pp. 1567–1576. IEEE Press, Los Alamitos (2002)
7. Ahdi, F., Srinivasan, V., Chua, K.C.: Topology control for delay sensitive applications in wireless sensor networks. Mob. Netw. Appl. 12(5), 406–421 (2007)
8. Heinzelman, W.R., Chandrakasan, A., Balakrishnan, H.: An application-specific protocol architecture for wireless microsensor networks. IEEE Transactions on Wireless Communications 1(4), 660–670 (2002)
9. Yu, Y., Krishnamachari, B., Prasanna, V.K.: Energy-latency tradeoffs for data gathering in wireless sensor networks. In: Proceedings of the Twenty-third Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2004), pp. 244–255 (2004)
10. Lu, G., Sadagopan, N., Krishnamachari, B.: Delay efficient sleep scheduling in wireless sensor networks. In: Proceedings of the Twenty-forth Annual Joint Conference of the IEEE Computer and Communications Societies, INFOCOM 2005 (2005)
11. Dousse, O., Mannersalo, P., Thiran, P.: Latency of wireless sensor networks with uncoordinated power saving mechanisms. In: Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing (Mobihoc 2004), pp. 109–120. ACM Press, New York (2004)
12. Gamal, A.E., Nair, C., Prabhakar, B., Uysal-Biyikoglu, E., Zahedi, S.: Energy-efficient scheduling of packet transmissions over wireless networks. In: Proceedings of IEEE Infocom 2002, pp. 1773–1782. IEEE Press, Los Alamitos (2002)
13. Zorzi, M., Rao, R.: Geographic random forwarding (GeRaF) for ad hoc and sensor networks: multihop performance. IEEE Trans. on Mobile Computing 2(4), 337–348 (2003)
14. Elson, J., Estrin, D.: Time synchronization for wireless sensor networks. In: IPDPS 2001: Proceedings of the 15th International Parallel & Distributed Processing Symposium, Washington, DC, USA, p. 186. IEEE Computer Society, Los Alamitos (2001)
15. Leon-Garcia, A.: Probability and Random Processes for Electrical Engineering, 2nd edn. Addison-Wesley, Reading (1993)
16. Miller, L.E.: Distribution of link distances in a wireless network. Journal of Research of the National Institute of Standards and Technology 106(2), 401–412 (2001)
17. Comaniciu, C., Poor, H.: On the capacity of mobile ad hoc networks with delay constraints. In: Proceedings of the IEEE CAS Workshop on Wireless Communications and Networking (2002)

18. Bettstetter, C., Eberspacher, J.: Hop distances in homogeneous ad hoc networks. In: Proceedings of Vehicular Technology Conference, VTC 2003-Spring, vol. 4, pp. 2286–2290 (2003)
19. Wang, X.: QoS issues and QoS constrained design of wireless sensor networks. In: Department of Electrical and Computer Engineering and Computer Science of the College of Engineering, University of Cincinnati Ohio, USA (2006)
20. Krishnamachari, B., Estrin, D., Wicker, S.B.: The impact of data aggregation in wireless sensor networks. In: ICDCSW 2002: Proceedings of the 22nd International Conference on Distributed Computing Systems, Washington, DC, USA, pp. 575–578. IEEE Computer Society, Los Alamitos (2002)
21. Cormen, T.H., Stein, C., Rivest, R.L., Leiserson, C.E.: Introduction to Algorithms. McGraw-Hill Higher Education, New York (2001)
22. Mhatre, V.P., Rosenberg, C., Kofman, D., Mazumdar, R., Shroff, N.: A minimum cost heterogeneous sensor network with a lifetime constraint. IEEE Transactions on Mobile Computing 4(1), 4–15 (2005)
23. Lazos, L., Poovendran, R., Ritcey, J.A.: Analytic evaluation of target detection in heterogeneous wireless sensor networks. ACM Trans. Sen. Netw. 5(2), 1–38 (2009)
24. Meguerdichian, S., Koushanfar, F., Potkonjak, M., Srivastava, M.: Coverage problems in wireless ad-hoc sensor networks. In: Proceedings of IEEE INFOCOM, vol. 3, pp. 1380–1387 (2001)
25. Bettstetter, C.: On the minimum node degree and connectivity of a wireless multihop network. In: MobiHoc 2002: Proceedings of the 3rd ACM international symposium on Mobile ad hoc networking & computing, pp. 80–91. ACM Press, New York (2002)
26. Zuniga, M., Krishnamachari, B.: Analyzing the transitional region in low power wireless links. In: Proceedings of the First IEEE International Conference on Sensor and Ad hoc Communications and Networks (SECON). IEEE, Los Alamitos (2004)