Minimizing energy consumption within wireless sensors networks

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ABSTRACT
The use of sensor networks should keep developing, mainly in such fields as scientific, logistic, military or healthcare applications. However, sensor size represents a significant limitation mainly in terms of energy autonomy and therefore of life period, for the batteries have to be too tiny. This is the reason why intensive research is being conducted nowadays on how to control sensor energy consumption within a network, taking communications into account as a priority. For this purpose we propose a method to calculate energy consumption within linear wireless sensor networks, according to the data flow rate, the number of nodes and the distance between them. Furthermore, we have succeeded in reducing energy consumption within linear sensor networks made up with nodes featuring differing data flow rates.

Keywords: Wireless sensors networks, Clustering, Energy consummation, Routing..

1 INTRODUCTION

Wireless sensor networks are a novel technology emerging from embedded system, sensor technology and wireless networks. The rapid deployment, self-organization and fault tolerance characteristics of wireless sensor networks make them a very promising sensing technique for military, environmental and health applications [1]. However finite, generally irreplaceable power sources in sensor node limit lifetime of the whole system. Some researches have proven that sensor node expends maximum energy in data communication [2]. A sensor network is a distributed system made up with a large number of small sensors, equipments, low power transmitters-receivers, without a central processing unit. One of the major problems in these networks consists in reducing energy consumption to a minimum in such a way as to maximize a network life time [3]. Recent advances in the IC technology make it possible to produce micro-sensing devices that are equipped with processing, memory and wireless communication capabilities.

In Wireless Sensor Networks, WSNs, nodes are untethered and unattended. They are distributed across an area of interest and communicate among themselves in multiple hops, building an ad-hoc network. Nodes have limited and non-replenishable energy resources. There are special nodes named sink (or gateway) nodes, that are responsible for processing and storing the information collected by the network [4].The battery is an essential component in data acquisition. In general, it is neither replaceable nor rechargeable. It may be partially fed by energy generating units such as photo-voltaic cells. As it is small, it provides a limited quantity of energy of the order of 1 to 2J by node (acquisition). Thus, it limits the sensor life time and influences the overall network working process.

Energy is a factor of outmost importance in WSNs. To increase network lifetime, energy must be saved in every hardware and software solution composing the network architecture. According to the radio model proposed in [5], data communication is responsible for the greatest weight in the energy budget when compared with data sensing and processing. Therefore, it is desirable to use short-range instead of long-range communication between sensor nodes because of the transmission power required. In most WSN scenarios, events can be sensed by many source nodes near the phenomenon of interest and far away from the sink nodes. Then, the use of short-range communication leads obligatorily to data packets being forwarded through intermediate nodes along a multi-hop path [2].

This article develops a model for the multi-hop communication in a linear array of nodes. Energy consumption in the various multi-hops scenarios has been analyzed and optimized. This study uses a detailed model for the energy consumed by the radio link of each node and analyzes two topologies: the first one with equidistant nodes hop and the other one with optimal spaces between the last nodes. The article is organized as follows.

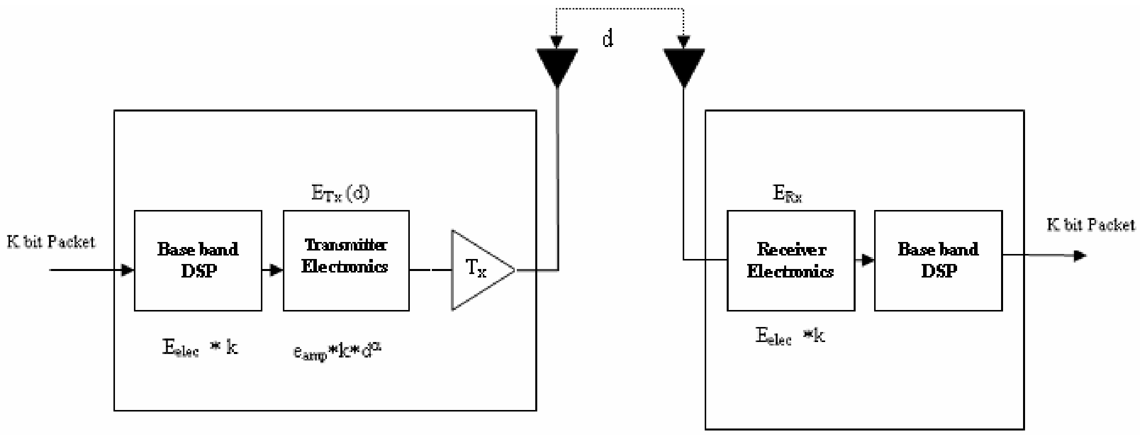

Figure 1: Energy consumption model for communications.

A model of basic energy consumption and communication topology is presented in section 2. The analysis of multi hops is performed in section 3 for different routing models and the optimal transmission range is analyzed in section 4. In section 5 the results based on the previous analyses are presented. MAC protocols are discussed in section 6 and finally the conclusion is presented in section 7.

2 ENERGY MODEL AND COMMUNICATION TOPOLOGY

2.1 Energy model

A sensor uses its energy in order to carry out three main functions: acquisition, communication and data processing.

1. Acquisition: the energy consumed to carry out the acquisition is generally negligible. Nevertheless, it varies in considerable proportions depending on the type of monitoring being carried out.

2. Communication: It consumes more energy than any other task. It covers the communications in terms of emission and reception. Figure 1 presents a transmission system model and the rules applied to controlled energy consumption [6].

3) Data processing: The energy consumed for the calculation operation is very low as compared with the communication energy. The energy needed to transmit 1 KB over a 100m distance is approximately equivalent to the energy necessary to carry out 3 million instructions at a speed of 100 million instructions per second (MIPS). This level might be much dependent on the circuitry installed in the nodes and the features requested.

$$E_{linear}(i) = [(2*i-1)(e_{elec} + ie_{amp}d_i^{\alpha}] \qquad (1)$$

where E_{elec} represents energy consumed in transmission, e_{amp} amplification, k the message length, d the transmitter/receiver distance and α a factor describing attenuation. To receive a message of k bits, the receiver then consumes:

$$E_{linear}(i) = [(2*i-1)(e_{elec} + ie_{amp}d_i^{\alpha}] \qquad (1)$$

2.2 Communication topology

We adopt a simple linear topology to discuss communication mode, as shown in figure 2 in order to simplify the analysis. At the left of the Figure 2, there are n sensor nodes arranged at intervals of r. The base station is on the right end. Using single hop mode, each node directly communicates with the base station; by contrast, each node communicates with the closest neighbor in multi-hop mode, nodes route data destined ultimately to the base station through intermediate nodes.

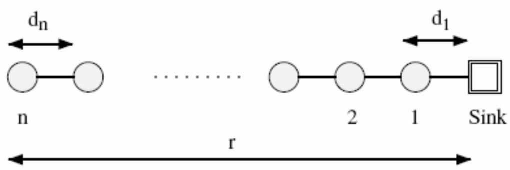

Figure 2: Multi-jump linear model featuring equal distances between the nodes.

3 ENERGY CONSUMPTION IN THE MULTIHOP SENSOR NETWORKS

Using equations (1) and (2), the energy consumed during data transmission from the source towards the destination going through intermediate nodes aligned in a row is written as:

$$E_{\text{linear}} = k\left\{\sum_{i=1}^{n}\left[2*e_{elec} + e_{amp}(d_i)^{\alpha}\right]\right\} \qquad (3)$$

E_{linear} is minimum when all the d_i are equal to D/n, when the number of hops is at its optimal value:

$$n_{opt} = \left\lfloor \frac{D}{d_{char}} \right\rfloor => d_{char} = \left(\frac{2 * e_{elec}}{e_{amp}(\alpha - 1)} \right)^{\frac{1}{\alpha}} \quad (4)$$

The optimal number of hops depends on the propagation loss coefficient α and the transmitter and receiver parameters [9,1]. By replacing d_{char} in statement E_{linear}, we obtain the following relation:

$$E_{linear}^{opt} = m \left[\frac{2 * n_{opt} * e_{elec} * \alpha}{\alpha - 1} - e_{RC} \right] \quad (5)$$

In the linear sensor network, two possibilities arise for the probability of event occurrence:

1. First case: uniform number of data flow rate constant among the nodes. If each node detects the same number of events (that is the necessity to convey information towards the destination), then we can suppose that each node receives an event simultaneously. This means this node should take (n-1) information packets originating from nodes upstream, in addition to the transmission of its proper packet [7], [8].

2. Second case: data flow rate variable between nodes. If each node does not detect the same number of events, the average number of packets transmitted within the linear sensor network has to be calculated.

3.1 Packets relayed

If x_i stands for the number of events detected by a given node, the number of packets relayed by this node is given by:

$$P_i = n - i + x_i \alpha \quad (6)$$

Let us assume the existence of an underlying supervision protocol, in charge of building and updating the routing tables for nodes. Then the mean number of events seen by each node is:

$$n_e = [\sum_{i=1}^{n} x_i] / n \quad (7)$$

The average number of transmitted packets N_{Pack} at node i may be estimated as:

$$N_{Pack} = n - i + n_e \alpha \quad (8)$$

where n is the number of nodes within the linear sensor network and i the node under consideration.

Example 1: A sensor network made up with 20 nodes, of which 20 nodes simultaneously detect an event, applying equation (6) leads to N_{Pack} =n-i+1

Example 2: A sensor network made up with 20 nodes, of which 15 nodes simultaneously detect an event and 5 simultaneously detect five events, applying equation ([6) leads to N_{Pack} =n-i+2.

3.2 Total energy cost for the system

From the average number of transmitted packets, the average energy consumed within the linear sensor network may be computed as:

$$E_{linear-bit} = -ne_{RC} + \sum_{i=1}^{n} \left[\left(e_{TC} + e_{RC} + e_{TA}(d_i)^{\alpha} \right) * N_{Pack} \right] \quad (9)$$

4 OPTIMAL TRANSMISSION RANGE

Bhardwaj et a1. [10] have shown that energy consumption within the multi-hop networks can be reduced by adjusting the distances between the n nodes which transmit the signal. But, if each node of the linear chain transmits data, this will be impossible. The distribution of the distances d_i between the nodes can be analyzed in order to minimize the energy consumption in this particular case. For all the nodes involved in the transmission scenario, the total energy consumption is presented in equation (8).

E_{linear} will now be minimized using the constraint $D = \sum_{i=1}^{n} d_i$, equivalent to the following formula:

$$L = e_{TA} \sum_{i=1}^{n} \left[N_{pack} (d_i)^{\alpha} \right] - \lambda \left(\sum_{i=1}^{n} d_i - D \right) \quad (10)$$

where λ is the Lagrange's multiplier. Equating the partial derivates of L with respect to the d_i to zero, it follows that:

$$\frac{\partial L}{\partial d_i} = e_{TA} . \alpha . N_{pack} (d_i)^{\alpha - 1} - \lambda = 0 \quad (11)$$

$$d_i = \left(\frac{\lambda}{e_{TA} . \alpha . N_{pack}} \right)^{\frac{1}{\alpha - 1}} \quad (12)$$

Using the condition $D = \sum_{i=1}^{n} d_i$ the value of λ can be obtained from equation (12). Thus, for α = 2 the values for d_i are found to be:

$$d_i = \frac{D}{\left(\sum_{i=1}^{n} (1/i)\right) N_{pack}} \quad (13)$$

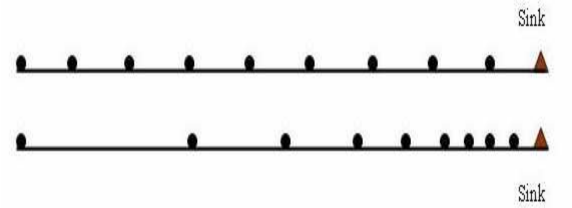

Figure 3: Linear and non linear sensor networks.

In [8, 12, 13], the energy consumption per packet sent consumed at node i for linear arrays of equally spaced nodes discussed is computed. In our approach the energy consumption per packet sent consumed at node i for linear arrays with unequal data flow rate ca be calculated by the following equation:

$$E_{linear}(i) = [(2 * N_{pack} - 1).e_{elec} + N_{pack}.e_{amp}.d_i^{\alpha}] \quad (14)$$

5 SIMULATIONS AND RESULTS

A sensor network made up from 30 nodes distributed over a 1000 m distance is simulated here, with parameters e_{elec} = 50 nJ/bit, e_{amp} = 100 pJ/bit/m^2, α=2,using Matlab™. Let us notice that this implies a 33.33 m distance between nodes in the equidistant case.

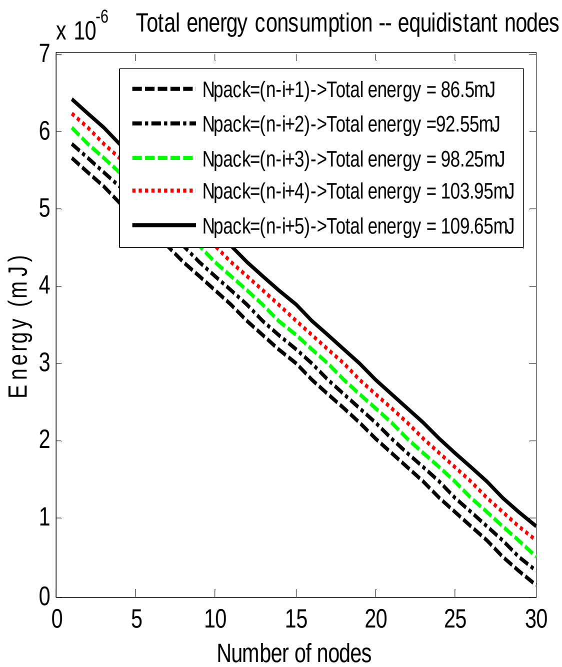

Figure 4: Energy consumed with transmission distances.

The cases where the d_i are equidistant or not are again considered here. Using equation (14), the results for optimal distances between nodes given in table I are obtained.

Table 1: OPTIMAL DISTANCES BETWEEN NODES.

n-i+1	n-i+2	n-i+3	n-i+4	n-i+5
8,3438	10.656	12.214	13.435	14.454
8.6315	11.011	12.608	13.855	14.892
8,9398	11.391	13.028	14.302	15.357
9,2709	11.798	13.478	14.779	15.853
9,6274	12.235	13.959	15.289	16.381
10,013	12.705	14.476	15.835	16.946
10,43	13.213	15.033	16.421	17.551
10,883	13.764	15.634	17.053	18.201
11,378	14.362	16.286	17.735	18.901
11.92	15.015	16.994	18.474	19.657
12.516	15.73	17.766	19.277	20.476
13.174	16.517	18.612	20.153	21.367
13.906	17.386	19.543	21.113	22.338
14.724	18.352	20.571	22.168	23.401
15.645	19.431	21.714	22.335	24.572
16.688	20.646	22.991	24.632	25.865
17.88	22.022	24.428	26.08	27.302
19.255	23.593	26.057	27.71	28.908
20.859	25.41	27.918	29.558	30.714
22.756	27.528	30.066	31.559	32.762
25.031	30.03	32.571	34.105	35.102
27.813	33.033	35.532	36.947	37.802
31.289	36.704	39.085	40.306	40.953
35.759	41.292	43.428	44.337	44.675
41.719	47.19	48.857	49.236	49.143
50.063	55.056	55.836	55.421	54.603
62.587	66.067	65.142	63.338	60.429
83.438	82.583	78.171	73.895	70.204
125.16	110.11	97.714	88.674	81.905
250.31	165.17	130.28	110.84	98.286

Fig. 4 presents the energy by each node in a sensor network with equidistant nodes, is obtained using equation (14) and with all d_i fixed to 33.33 m, for, respectively, uniform or non-uniform mean numbers of events detected by each node. It is worthwhile noting that the total energy consumption when each node doesn't detect the same number of events (variable flow rates) is slightly higher than that in the uniform number of events bottom curve case.

Fig. 5 presents the amount of energy consumed by each individual node within a sensor network featuring optimal distances shown in table I between the nodes, obtained from equation (14), for uniform or non-uniform number of detected events.

It must be noticed that the total energy consumption within the network has been reduced by 38% when Npack=(n-i+1), 26% when Npack=(n-i+2), 21% when Npack=(n-i+3), 17% when Npack=(n-i+4) and 15% when Npack=(n-i+5) following the approach proposed in section IV

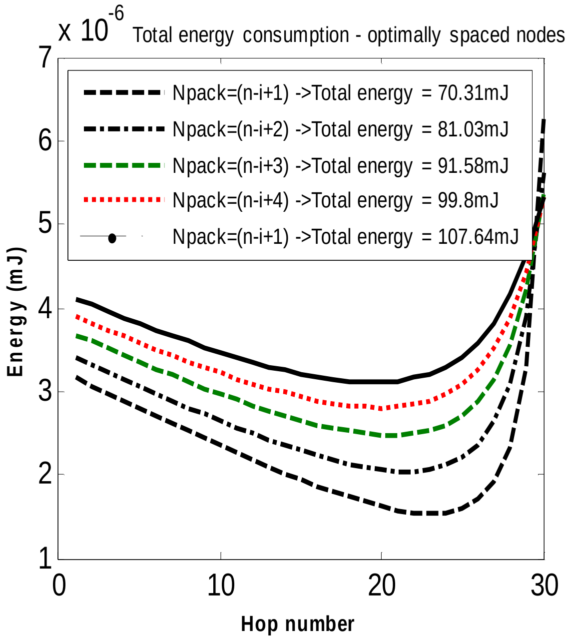

Figure 5: Energy consumed with optimal transmission distances.

Comparing figures 4 and 5,it is evident that the nodes far from the sink consume significantly less energy for optimally spaced nodes than for equally spaced nodes. This is in fact due to their smaller separation. The consumed energy tends to decrease with hop number in figure 5 in figure 4, thanks to a lower number of packets to be transmitted.

However the distance between nodes is an increasing function of hop number, which tends to increase the energy consumption. So it is surprising that, starting at the some hop number, the consumed energy sharply increases and this for few last nodes. However the overall energy consumption tends to be smaller for optimally spaced nodes than for equally spaced ones.

6 DISCUSSION ON MAC PROTOCOLS

Shelby et Al [10, 11] described the impact of MAC protocols on the energy model used in this paper, namely Nonpersitent CSMA , S-MAC [9] and NanoMAC. Fig. and Fig7 presents Transmission and Receive energy consumption model for nanoMAC.

Nonpersitent CSMA [10, 11, 6, 12] is a well known, relatively well performing MAC protocol in almost any scenario. It gives the worst-case energy consumption that any sensor MAC protocol should outperform. S-MAC is the current sensor MAC benchmark protocol which is used to highlight some of the faults of traditionally designed sensor MAC protocols.

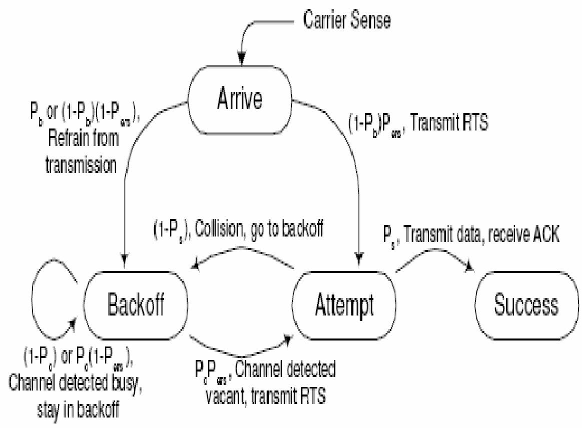

Figure 6: Transmission energy consumption model for nanoMAC.

They compared these to nanoMAC, a protocol designed to operate in a sensor networking environment. They have analytically investigated a cross layer energy consumption model with realistic radio transceiver characteristics, three MAC protocols and a linear network model suitable for many sensor network protocols in steady state. Based on this analysis, they have discovered many interesting results that relate to single hops vs. Multi-hop communications and MAC protocol features.

1) When a realistic radio model is applied for a sensor network, they discovered that, assuming feasible transmission distances, single-hop communications can be more efficient than multi-hop in the energy perspective.

2) A well designed sensor MAC protocol has a behavior similar to the ideal MAC protocol, but the

energy consumption is two orders of magnitude higher.

3) There are some inherent flaws in adapting existing ad hoc MAC protocols to sensor networks. Idle listening and overhearing avoidance are important factors as already discussed in other publications, such as [14, 11], but also any listening that is not absolutely necessary, like listening for the RTS in S-MAC, decreases the energy performance of a sensor MAC.

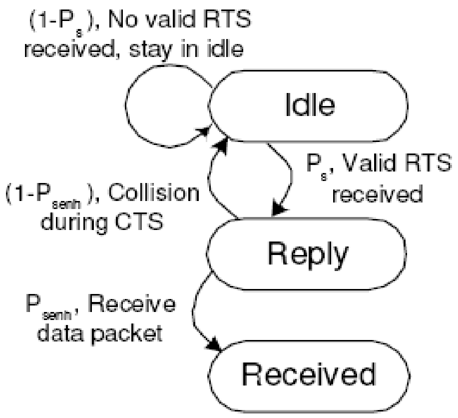

Figure 7: Receive energy consumption model for nanoMAC.

7 CONCLUSION

In this work, it has been shown that the total energy consumption in a linear sensor network may be reduced (by 15% to 38%) using optimal spacing between nodes.

The model used suggests that the transmitter can dynamically adjust its transmission power, in such a way that the requested signal to noise ratio may be warranted at the receiver. This work will be pursuited by studying the scenarios which determine the transmission power and finding the efficient data coding and modulation techniques for practical applications of wireless sensor network (WSNs).

Our analytical results will also be compared with the results of physical measurements. The influence of different routing models and protocols for sensor networks on energy consumption will also be considered. Moreover an extension to 2D array of sensors is also planned

8 REFERENCES

[1] F.Akyildiz I F, Su W and Sankarsubramaniam Y 2002 Wireless sensor networks: a survey Computer Networks 38 393-422

[2] C.-Y. Chong and S. Kumar,"Sensor networks: Evolution, opportunities, and challenges", Proc. IEEE, Vol. 91, No. 8, pp.1247-1256, 2003.

[3] Hill, M. Horton, R. Kling and L. Krishnamurthy,"The Platforms Enabling Wireless Sensor Networks", Communications of the ACM, Vol. 47, No. 6, 2004.

[4] Teixeira, I., de Rezende, J. F., and Pedroza, A.C.P. - "Wireless Sensor Network: Improving the Network Energy Consumption", in XXI Simpõsio Brasileiro de Telecomunicações - SBT'2004, Belém, Brazil, September 2004.

[5] W.R.Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy efficient communication protocol for wireless microsensor networks", Proceedings of the 33rd IEEE Hawaii International Conference on System Sciences (HICSS), pp. 1-10, Jan. 2000.

[6] W. Li. and C. G. Cassandras, "Sensor Networks and Cooperative Control", European Journal of Control, Vol. 11, No. 4-5, pp. 436-463, 2005.

[7] H. Karvonen, Z. Shelby, and C.A. Pomalaza-R´aez, "Coding for Energy Efficient Wireless Embedded Networks" ,Proceedings of the International Workshop on Wireless Ad Hoc Networks, May 31 - June 3, 2004, Oulu, Finland.

[8] J. Haapola, Z. Shelby, C.A. Pomalaza-R´aez, and P. Mahonen,"Multihop Medium Access Control for WSNs: An Energy Analysis Model", EURASIP Journal of Wireless Communications and Networking, Vol. 2005, No. 4, pp. 523-540, September 2005.

[9] Q Gao, K J Blow, D J Holding, I Marshall, and X H Peng,"Radio Range Adjustment for Energy Efficient WirelessSensor Networks", Ad-Hoc Networks, Vol. 4, No. 1, pp. 75-82, 2006.

[10] M. Bhardwaj, A. Chandrakasan, and T. Garnett, Upper bounds on the lifetime of sensor networks, Proceedings of the IEEE ICC, pp. 785-790, 2001.

[11] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks", IEEE/ACM Transactions on Networking, vol. 12, pp. 493-506, June 2004.

[12] J. Haapola, Low-power wireless measurement system for physics sensors, Master Thesis, Department of Physical Sciences, University of Oulu, Oulu, Finland, 2002, unpublished, available online on http://www.ee.oulu.fi/jhaapola/.

[13] J. Haapola, Z. Shelby, C. Pomalaza-R´aez, and P. M'ah'onen, Cross-layer energy analysis of multi-hop wireless sensor networks, in Proc. 2nd European Workshop on Wireless Sensor Networks (EWSN 05), pp. 3344, Istanbul, Turkey, January February 2005.

[14] L. Kleinrock and F. A. Tobagi, Packet switching in radio channels: Part ICarrier sense multiple-access modes and their throughput-delay characteristics, IEEE Trans. Commun., vol. 23, no. 12, pp. 1400? 1416-1975.