Reliable Source Based Reactive Routing Protocol for Wireless Sensor Networks

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***Abstract*—Wireless sensor networks (WSNs) are characterized by scarcity of resources and highly unreliable wireless channels, whereby minimizing energy-consumption is a key issue in design of communication protocols for the battery powered sensor nodes. The work in this paper addresses the problem of finding energy-efficient routes for delivery of packets through multihop communication with modification to the standard dynamic source routing (DSR) algorithm, aiming to prolong the overall network lifetime in WSN. Simulation based performance evaluation is presented for the energy-efficient DSR (EEDSR) protocol in comparison with the DSR protocol. The simulation results reveal improved performance on energy-efficiency and network lifetime when using the new routing metric which incorporates link reliability for establishment of minimum energy routes for reliable delivery of packets; illustrating therefore that routing algorithms in WSNs should consider not only hopcount and the distance of individual links along a route, but also quality of the routes in terms error rates.**

***Index Terms*—energy-efficiency, error-rates, link reliability, retransmissions, routing protocols, sensor networks.**

I. INTRODUCTION

Over the last few years, wireless sensor networks (WSNs) have drawn attention from the research community with increasing popularity. The merging of advanced computing and wireless communication technologies made WSNs a possible realization, with unique applications requirements leading to diversity in hardware and software designs. Implementation and deployment of WSN applications present various design challenges, many of which are inherent to the time-varying characteristics associated with the wireless transmission media and scarcity of resources imposed by the decreasing size of sensor nodes [1]. However, the distributed and decentralized nature of WSNs, together with operation without infrastructure support and administration evoked a considerable research work and effort to improve their performance in various applications. Being distributed in nature, WSNs can be highly robust with large node redundancy for reliable communication, eliminating single points-of-failure and performance bottle-necks in network deployments [2]. It follows therefore that communication protocols for WSNs should be designed to be self-organizing and self-configuring. Moreover, the protocols should be highly adaptive to address the dynamic and non-uniform nature of the highly unreliable wireless channel links; as such channels degrade the quality of transmissions, resulting in poor overall network performance [3]. Understanding the trade-offs between power consumption, signal processing and wireless communication is a nontrivial and unavoidable design issue as the sensor nodes have severe scarcity of resources in terms of battery-power, available memory, processing and communication capabilities [1]-[2], [4].

The most important challenge in design and implementation of communication protocols for WSNs is minimizing energy consumption without compromising network performance [5]. Power management solutions in literature include transmission power control (TPC) techniques which adapt the transmission power to channel propagation and interference characteristics for the wireless links; aiming to make each link as energy-efficient as possible [6]. Hence, the previous works in literature illustrated that TPC techniques can significantly improve network capacity while minimizing energy consumption during data transmissions [1], [3], [5], [7]-[10]. These works demonstrate that network capacity can be improved by transmitting a packet to a nearest neighbor node in forward progress direction to a destination node, with the intuition that reducing transmission range allows for more concurrent transmissions to occur within a neighborhood.

The network layer is one of the most investigated research topics with many routing algorithms and protocols which have been proposed for WSN communications [11]-[17]. In particular, the routing protocols suitable for WSNs should ensure that network connectivity is maintained for as long as possible, and the energy status of the entire network is of the same order for graceful degradation of network operation [12], [14], [16]-[18]. Most of the existing energy optimizing routing protocols aim to find optimal routes, and then burn the energy of the nodes along such routes; leaving the network with a wide disparity in energy levels of the nodes, which eventually leads to various disconnected network segments [6], [11], [13], [15], [18]. Thus, as nodes run out of battery power, the connectivity decreases and the network finally becomes partitioned and dysfunctional.

The rest of this paper is organized as follows: Section II discusses the problem description and formulation motivating the work presented in this paper. Section III presents the system model adopted for the performed simulation studies, followed by Section IV which presents the simulation based performance evaluation of the routing protocols. Finally, Section V summarizes the main points on which the work presented in this paper is concluded.

II. MOTIVATION AND PROBLEM FORMULATION

Routing is one of the main problems in WSN communications for which a remarkable amount of work has been accomplished on development of energy aware routing protocols which aim to minimize energy consumption by exploiting the fact that the required transmission power over a wireless channel link is a non-linear function of distance; in which case using a route with large number of short distance hops may consume less energy than another route with few large distance hops per node, assuming adaptive transmission power levels [4]-[7], [10]. The transmitted power P_{Tx} over a wireless link with distance d is subject to attenuation such that the received power P_{Rx} is proportional to d^n according to the following expression [17]:

$$P_{Rx} \propto \frac{P_{Tx}}{d^n}, \quad n \geq 2 \tag{1}$$

where n is the distance loss attenuation factor. Ensuring energy-efficient routing in WSNs faces many challenges due to both wireless communication effects and the existing peculiarities associated with this type of networks. These challenges preclude the existing routing protocols developed for traditional wireless ad hoc networks from being used in WSNs. Instead, careful design approaches are required to build novel routing protocols that require the least energy consumption for reliable end-to-end packet delivery [11]. Although energy-efficient communication in WSNs has been addressed in the literature, the area still remains a vastly unexplored domain whereby to this end, energy consumption is still the main concern in the development of routing protocol for WSNs. Because of the limited energy resources from the sensor nodes, data need to be delivered in the most energy-efficient manner without compromising the accuracy of the information content [11], [14], [16]-[17], [19]. In many WSN applications, network-survivability is a critical issue, in which optimizing energy consumption is mandatory in order to achieve efficient operation and maximum network lifetime.

A. *Minimum Energy Reliable Route Costs*

This subsection presents the energy cost analysis for transmission of data packets along a route in a WSN. For any link $link(u,v)$ between any two nodes node u and node v, $E(u,v)$ represents the energy required to transmit a packet across the link between the nodes. Let h be the total number of relay nodes between a source node n and the sink node D indexed as $i: i = \{1, 2, \ldots, h\}$, with node i representing the relay node i along the route. The total energy $E(n,D)$ expended for delivery of a single packet without retransmission from node n to the sink node D is given by

$$E(n,D) = \sum_{i=1}^{h+1} E(u,v)_i. \tag{2}$$

Based on (2) above, an energy-efficient routing algorithm is the one which uses a route with the lowest possible $E(n,D)$ for packet transmission among all the available routes. Using poor quality links along the route increases energy overhead for a reliable delivery of packets as a result of necessary retransmissions [20]. Assuming each of the links along any route p has an independent link error probability $P_r link(u,v)$, the total error probability $P_r(p)$ for end-to-end reliability over the entire route is given by the following expression [19]:

$$P_r(p) = 1 - \prod_{i=1}^{h+1} (1 - P_r link(u,v)_i) \tag{3}$$

In order to fully recover an erroneous packet, it is assumed that the number of transmissions (together with possible retransmissions) required for successful delivery of a packet from source node n to the sink node D is a random variable X with a geometric distribution such that [19]

$$P_r\{X = k\} = \prod_{i=1}^{k-1} P_r(p)_i \times \left(1 - P_r(p)\right), \qquad \forall\, k. \tag{4}$$

It follows therefore that the mean number of individual packet transmissions $E[X]$ for successful delivery of each packet is given by the following expression [19]:

$$E[X] = \frac{1}{1 - P_r(p)}. \tag{5}$$

From (5) above, it can be deduced that the number of required transmissions for reliable communication (transmission of a packet without errors) is the reciprocal of the probability of successful delivery of a packet for each transmission. The total energy consumption $E(n,D)$ based on (2) required for the successful transmission of a packet for end-to-end reliable communication is given by the following [17]:

$$\begin{aligned} E(n,D) &= \sum_{i=1}^{h+1} \frac{E(u,v)_i}{\left(1 - P_r(p)\right)} \\ &= \sum_{i=1}^{h+1} \frac{E(u,v)_i}{\prod_{i=1}^{h+1}(1 - P_r link(u,v)_i)} \end{aligned} \tag{6}$$

In the case of hop-by-hop reliability, transmission error on a specific link entails a need for retransmissions on that link in particular [19]. Hence, energy spent on the link as a result of retransmissions is independent of the errors encountered on other links. Assuming the number of retransmissions on each link is independent of other links with a geometric distribution, the energy required to transmit a packet from source node n to the sink node D is given by [17]

$$E(n,D) = \sum_{i=1}^{h+1} \frac{E(u,v)_i}{(1 - P_r link(u,v)_i) \times (h+1)}. \tag{7}$$

Equation (6) and (7) above illustrates that the energy required for reliable transmission of packets increases with the number of intermediate nodes h through which the packet is relayed.

B. Modeling Packet Error Rate (PER) for Reliable Routes

The wireless channel model is used for generating packet errors during transmissions. A transmitted packet is simply marked erroneous if the ratio of the packet's signal strength at the receiver node as compared with all the noise and interference is below some threshold. Hence, a packet from a transmitting node u can only be received by node v only if the signal-to-noise interference ratio $SNIR(u,v)$ is above some threshold $SNIR_{Th}$ that signifies the QoS requirement for the link to correctly receive a transmitted packet, given by [21]

$$SNIR(u,v)_{dB} = 10\log_{10}\left(\frac{P_{Rx}}{\eta + \sum_{i=1}^{K} I_i} \times PG\right) \quad (8)$$

where P_{Rx} is the received signal strength, η is the noise power, I_i is the inter-node interference from node i, and K is the number of neighbors that contribute to the interference, and PG is the direct sequence spread-spectrum (DSSS) processing gain given by the ratio W/R_b; where W is the spreading bandwidth and R_b is the bit-rate, which is dependent on coding and modulation scheme used. For each node, K is a random variable since the number of interfering nodes varies from time to time. The higher the $SNIR$ in (8), the better the wireless channel link quality.

Following the work in [22], similar assumptions are also made in this paper about the additive white Gaussian noise and binary phase shift keying (BPSK) modulation scheme to estimate the average BER experienced by each node for the received packet, given by the following expression:

$$\begin{aligned} BER &= \frac{1}{2} \times erfc\left(\sqrt{\frac{P_{Rx}}{(\eta + \sum_{i=1}^{K} I_i)} \times \frac{W}{R_b}}\right) \\ &= \frac{1}{2} \times erfc\left(\sqrt{SNIR}\right) \end{aligned} \quad (9)$$

where the $erfc$ is the complementary error function [23]. However, the main focus of the work in this paper is not on the details of any specific modulation scheme, but to study the dependence of packet error rates on the received power levels. A packet of length L-bits through a link between node u and node v has packet error rate (PER) given by [19]

$$PER = 1 - \prod_{i=1}^{L}(1 - BER). \quad (10)$$

The estimated PER in (10) provides information about quality of the wireless channel link $P_r(link(u,v))$ traversed by the transmitted packet from a source node u to a receiver node v.

C. Routing Cost Function

The use of physical layer information aids the routing protocol to avoid highly error-prone routes during packet transmissions. The protocol operations extend our previous work in [19] for the exchange of routing information. In this work, additional fields for the route request (RREQ) packet and the route reply (RREP) packet are introduced to record the PER and the cumulative energy $E(n,D)$ in (2) for all the links comprising a route the destination node.

During route discovery phase, a source node initializes both the $E(n,D)$ and PER fields to 0 and 1 respectively. On receiving the RREQ packet, the intermediate nodes update the fields accordingly. The energy requirements information is obtained with the aid of the neighborhood information [21]. This information records the energy required to successfully transmit a packet to the neighbor node as a function of distance separating the nodes. A node initiating a reply back to the source node inserts the recorded PER and $E(n,D)$ values form the RREQ packet into the RREP packet. The source node calculates the cost associated with every route according to (6) on receiving the RREP packet, and inserts the route with its associated cost into the route cache. Each node can record a maximum of three routes for redundancy in case of routes failures. A minimum cost route is selected as a primary route and used for packet transmissions.

III. SYSTEM MODEL

A. Network Model

We represent a WSN by a directed connectivity graph $G(N,E)$, where N is a set of all the nodes in a WSN and E is the set of all the links between pairs of nodes that can communicate directly. Each sensor node $n \in N$ has an isotropic transmission radius $R_t(n)$ and sensing radius $R_s(n)$. It is assumed that all the nodes have equal $R_t(n)$, which determines the set of nodes with which each node can directly communicate; referred to as neighbor nodes. The set of nodes which are within $R_t(n)$ are represented by $N_{nbr}(n)$ while all the other nodes are represented by $\overline{N}_{nbr}(n)$. Bidirectional and symmetric links exist between every source node and a neighbor node $m \in N_{nbr}(n)$. Therefore, for any two directly connected nodes$\{u,v\} \in N$, $link(u,v)$ is identical and symmetric to $link(v,u)$. Each sensor node n has a set of routes represented by $Routes(n)$ to the sink node, with each route $p_i(n) \in Routes(n)$ being the i-th route in the route cache. For simplicity, $R_t(n)$ and $R_s(n)$are assumed to be equal for each sensor node throughout this paper.

B. Channel Model

Wireless channel model emulates the time-varying and non uniform characteristics of a transmission channel, whereby transmitted signal strength is subject to distance loss, shadowing and multi-path fading as it propagates through the air interface. Exponential path loss model with log-normal fading effect for the wireless channel between any two nodes is considered in this work. This channel model has been experimentally shown to accurately model the low power communication in WSNs as illustrated by the work previously conducted and reported in [24]-[26]. Following these reports, the path-loss $PL(d)$ at distance d is given by

$$PL(d)dB = \overline{PL}(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad (11)$$

where $\overline{PL}(d_0)$ is the path-loss in dB at distance d_0 (whereby

d_0= 1meter), n is the path-loss attenuation factor and X_σ is a zero mean Gaussian random variable with a standard deviation of σ (in dB). In this work, a plain ground is considered for the values of n and σ to be 3.12 and 1.83 respectively, as indicated by the work in [26] for a one slope path-loss propagation model as shown in Table I below. The received signal strength $P_{Rx}(d)$ is therefore given by

$$P_{Rx}(d) = P_{Tx} - PL(d) \qquad (12)$$

where d is the distance between a transmitting node and a receiving node. The expression in (12) above provides the received signal strength as a function of distance separating the two communicating nodes.

C. *Traffic Model*

In this work, each node generates data messages for the sink node. We assume that the message arrivals follow an independent and identically distributed (*i.i.d.*) Poisson process with varying number of packets per message but identical packet lengths fixed at 64 bytes. In addition to the messages generated locally by each node, any node can cooperatively relay packets originated by other nodes through multihop communication. Further, we assume that the distribution for the number of the messages arrivals X generated by each node n during the time interval between t_i and $(t_i + T)$ with the average message arrival rate of λ_n is given by

$$P(X = k) = \frac{(\lambda_n T)^k}{k!} e^{-\lambda_n T}, \qquad k > 0, \qquad (13)$$

where k is a non-negative integer. We assume also that the inter-arrival times for the Poisson traffic generator have an exponential distribution with a probability density function $f_X(x) = \lambda_n e^{-\lambda_n x}\, for\ x \geq 0$. Without loss of generality, two sources of traffic for each node can be considered according to the above description, λ_{nn} and λ_{mn}. Following [13], the total packet arrival rate λ_n at each node n is given by

$$\lambda_n = \lambda_{nn} + \sum_{m \in N_{nbr}(n)} \lambda_{mn}, \qquad m = 1, \ldots, N_{nbr} \quad (14)$$

where m is any neighbor node to node n and N_{nbr} is the number of neighbors. Evidently, the nodes which are located in close vicinity to the sink node will have a high duty cycle compared to other nodes further away. Traffic load in a WSN depends heavily on the application for which the network is deployed. Therefore proper assumptions of realistic traffic models for performance evaluation of protocols in WSNs are important to ensure accurate modeling and analysis, so that the protocols are designed as effectively as possible [27].

TABLE I: CHANNEL MODEL PARAMETERS

Parameter	**Value**
Propagation model	log-normal
Path-loss exponent (n)	3.12
Standard deviation (σ)	1.83

IV. SIMULATION AND RESULTS

A. *Simulation Setup*

This section presents performance analysis of the proposed modification to the standard DSR protocol through simulation studies. We developed a discrete event driven simulation program for WSNs implemented in C++ language. Table II shows simulation parameters based a low cost and highly integrated Chipcon CC2420 radio transceiver module that was designed for low power and low voltage wireless applications, which complies with the IEEE 802.15.4 standard [28]. The CC2420 transceiver has been widely used in literature and practical experimentations in WSNs [5], [7], [13], [20]-[21].

B. *Performance Metrics*

The following are metrics considered for the work in this paper for evaluation of the proposed routing protocols:

- *Total energy consumption*: A measure of the total energy consumed by sensor nodes in a WSN, which is provides efficiency of the routing protocols on energy consumption during packet transmissions.
- *Routing control packets energy*: The total energy consumption associated with the exchange of routing control packets during route establishment, which provides the overhead on energy consumption as a result of routing information exchange.
- *Network lifetime*: The time it takes for 15% of the nodes in a WSN to run out of energy. In literature, network lifetime refers to how long it takes for a WSN to become partitioned and dysfunctional due to energy depletion from the sensor nodes batteries [12], [16].
- *Average network throughput*: The average number of data packets successfully received by the sink node per unit time, measured in kbps, which provides the measure of the effectiveness of the routing protocols on delivery of packets to the sink node in a WSN.

TABLE II: SIMULATION PARAMETERS

Parameters	**Values**
Sensor network field	$500m$ x $500m$
Number of nodes (N)	100 Nodes
Transmission range ($R_t(n)$)	15 Meters radius
Current consumption (Rx)	18.8 mA
Current consumption (Tx)	17.4 mA
Current consumption ($IDLE$)	426.0 µA
Data rate	250 kbps
Packet size	64 Bytes
Routing control packet	32 Bytes

C. Simulation Results and Discussion

The simulation study is performed for increasing message arrival rate scaling from 0.1 to 1.0 messages per second for 300 seconds, and the results were averaged over 10^3 simulation runs. Table III presents the average values for each of the performance metrics used in this work; which in general, illustrate improved performance and efficiency by the EEDSR protocol. The results on this table also show that the energy consumed as a result of routing control packets alone is significant. Hence, the exchange of control packets must be taken into consideration in design of energy-efficient routing protocols. The simulation results in Fig. 1 and Fig. 2 illustrate further, improved performance on energy consumption by the EEDSR protocol in comparison with the standard DSR protocol. The introduction of the new routing cost function which includes cumulative-energy and error-rates along a route by the EEDSR protocol minimizes energy consumption by using energy-efficient routes which are also less prone to route breakages during transmission of packets.

Furthermore, through the caching of multiple redundant routes to the same destination in the EEDSR protocol, alternative routes are readily available in case of primary route failure during packet transmissions without introducing more overhead on energy consumption which would otherwise be incurred during establishment of an alternative route. Fig. 3 presents results for network-lifetime as described in the previous subsection, in which the EEDSR protocol still outperforms the standard DSR protocol; conforming to the results in Fig. 1 and Fig 2 on energy consumption, in which case the increase in energy consumption leads to faster depletion of energy from individual nodes' batteries, which in turn reduces network-lifetime. Finally, Fig. 4 illustrate that the EEDSR protocol improves energy-efficiency without compromising network performance in terms of throughput, whereby improvement on network throughput in shown. The key reason for the improved performance by the EEDSR protocol is the incorporation of cumulative-energy and link error-rate metrics for assessment of available routes, as well as caching of multiple routes for the destination node.

TABLE III: AVERAGE PERFORMANCE EVALUATION RESULTS

Parameters	**DSR Protocol**	**EEDSR Protocol**
Total energy consumption	69.745 J	56.987 J
Control packets energy	8.1518 J	7.2091 J
Network lifetime	243.5 sec	270.7 sec
Network throughput	186.6 kbps	213.5 kbps

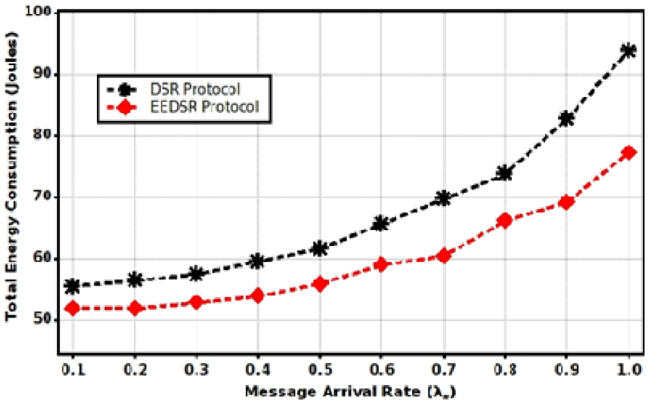

Figure 1: Total energy consumption versus arrival rate

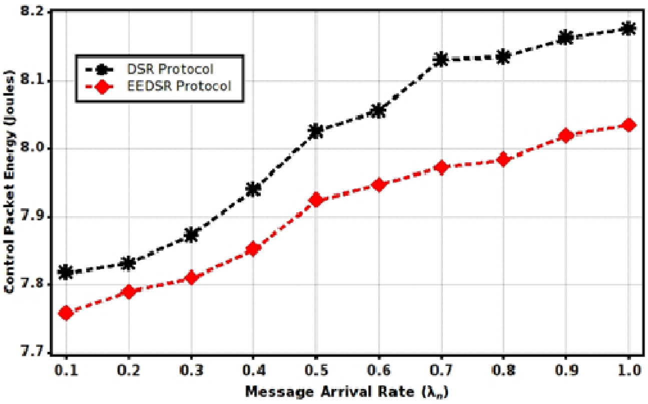

Figure 2: Routing control packets energy versus arrival rate

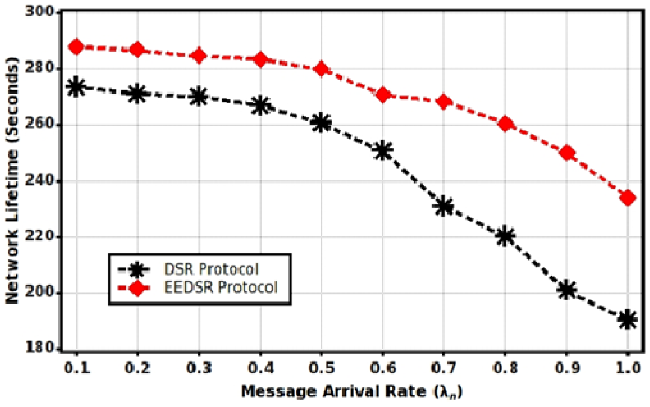

Figure 3: Network lifetime versus message arrival rate

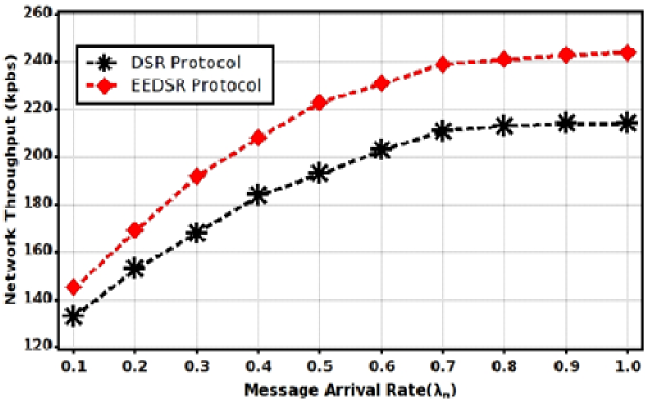

Figure 4: Average network throughput versus arrival rate.

V. CONCLUSION

Contrary to traditional networks, WSNs are characterized by low energy requirements and unreliable wireless channel links. Using such links may lead to faster depletion of energy from the sensor nodes batteries and reduce the overall network performance. The work in this paper presented the EEDSR protocol which aims to improve performance of the standard DSR protocol by taking into account, energy cost and reliability of wireless channel links for assessment of routes in order to achieve energy-efficient and reliable delivery of packets in WSN communications. The simulation results reveal improved performance by the EDSR protocol in comparison to the standard DSR protocol. Based on the presented results, it can be concluded that routing protocols must consider not only the distance and hopcount, but also the quality of wireless channel links for assessment of routes; whereby the cost of using a particular route includes also, the total transmission energy with possible retransmissions to ensure reliable delivery of packets in the network

REFERENCES

[1] A.J. Goldsmith and S.B. Wicker, “Design challenges for energy constrained ad hoc wireless networks,” *IEEE Transactions on Wireless Communications*, vol. 9, no. 4, pp. 8-27, Aug. 2004.

[2] G.A. Shah, W. Liang and X. Shen, “Cross-layer design for QoS support in wireless multimedia sensor networks,” in *proc. of the IEEE GLOBECOM’2010*, pp. 1-5, Dec. 2010.

[3] V. Kawadia and P.R. Kumar, “A cautionary perspective on cross layer design,” *IEEE Transactions on Wireless Communications,* vol. 12, no. 1, pp. 3-11, Feb. 2005.

[4] U.C. Kozat, I. Koutsopoulos and L. Tassiulas, “Cross-layer design for power efficiency and QoS provisioning in multi-hop wireless network,” *IEEE Transactions on Wireless Communications,* vol. 5, no. 11, pp. 3306-3315, Dec. 2006.

[5] R. Jurdak, P. Baldi, C.V. Lopes, "Adaptive low power listening for wireless sensor networks," *IEEE Transactions on Mobile Computing*, vol. 6, no. 8, pp. 988-1004, Jun. 2007.

[6] R. Cruz and A. Santhanam, “Optimal routing, link scheduling and power control in multi-hop wireless networks,” in *proc. IEEE INFOCOM’2003*, vol. 1, pp. 702-711, Mar. 2003.

[7] B. H. Calhoun *et al*., “Design considerations for ultra-low energy wireless microsensor nodes,” *IEEE Transactions on Computers*, vol. 54 no. 6, pp. 727-740, Jun. 2005.

[8] P. Gupta and P. R. Kumar, “The capacity of wireless networks,” *IEEE Transactions on Information Theory, vol.* 46, no. 2, pp. 388-404, Mar. 2000.

[9] T.C. Hou and V. O. K. Li, “Transmission range control in multiple packet radio networks,” *IEEE Transactions on Communications*, vol. 34, no. 1 pp. 38–44, Jan. 1986.

[10] R. Elbatt and A. Ephremides, “Joint scheduling and power control for wireless ad-hoc networks,” in *proc. IEEE INFOCOM’2004*, vol. 3, no. 1, pp. 74-85, Jan. 2004.

[11] F. Bouabdallah, N. Bouabdallah and R. Boutaba, “Cross layer design for energy conservation in wireless sensor networks,” *in proc. IEEE Int. Conf. on Communication,* pp. 1-6, Jun. 2009.

[12] J.H. Chang and L. Tassiulas "Maximum lifetime routing in wireless sensor networks*", IEEE/ACM Transactions on Networking*, vol. 12, no. 4, pp. 609-619, Sep. 2004.

[13] M.C. Vuran and I.F. Akyildiz, “XLP: A cross-layer protocol for efficient communication in wireless sensor networks,” *IEEE Transactions on Mobile Computing*, vol. 9, no. 11, pp. 1578-1591, Nov. 2010.

[14] Y. Liang, “Energy efficient, reliable cross-layer optimization routing protocol for wireless sensor networks,” in *proc. IEEE Int. Conf. ICIP’2010*, pp. 49- 496, Aug. 2010.

[15] H. Peng, Y. Ruan, “A new multiple routing algorithm for ad hoc networks,” in *proc. IEEE Int. Conf. Wireless Communications (WiCOMM’2008),* Dalian, pp. 1-4, Oct. 2008.

[16] H. Yousefi, M.H. Yeganeh and A. Movaghar, “Long lifetime routing in unreliable wireless sensor networks,” in *proc. IEEE ICNSC’2011*, Delft, pp. 457-462, ISBN: 978-1-4244-9570-2, Apr. 2011.

[17] S. Banerjee and A. Misra, “Minimum energy paths for reliable communication in multi-hop wireless networks,” in *proc. IEEE/ACM MobiHoc Conf.*, pp. 146-156, June 2002.

[18] X. Ren and H. Yu, “Multipath disjoint routing algorithm for ad hoc wireless sensor networks,” in *proc. IEEE Int. Symp. Object-Oriented Real-Time Dist. Comp.* (*ISORC’2005*), pp. 253-256, May 2005.

[19] S.C. Chabalala, T.N. Muddenahalli and F. Takawira, “Modified dynamic source routing for wireless sensor networks: end-to-end delay analysis,” in *proc. SATNAC’2011*, East-London, SA, Sept. 2011.

[20] I. F. Akyildiz, M. C. Vuran, and Ö. B. Akan, “A cross layer protocol for wireless sensor networks,” in *proc. IEEE CISS’06*, Princeton, NJ, USA, pp. 1102-1107, Mar. 2006.

[21] S.C. Chabalala, T.N. Muddenahalli and F. Takawira, “Cross-layer adaptive routing protocol for wireless sensor networks,” in *proc. IEEE AFRICON’2011*, Livingston, Zambia, Sep. 2011.

[22] S. Lee, B. Bhattacharjee, and S. Banerjee, “Efficient geographic routing in multihop wireless networks,” in *proc. the 6th IEEE/ACM Int. Symp. MobiHoc '2005*, New York, NY, USA, pp. 230-241, May 2005.

[23] S. Papavassiliou and L. Tassiulas, “Joint optimal channel, base station and power assignment for wireless access,” *IEEE/ACM Transactions on Networking*, vol. 4, No. 6, pp. 857-872, Dec. 1996.

[24] A. Martınez-Sala, *et al*, “An Accurate Radio Channel Model for Wireless Sensor Networks Simulation,” *Journal of Communications and Networks (JCN’2005),* vol. 7, no. 4, Dec. 2005.

[25] J.M. Molina-Garcia-Pardo, *et al*, "Channel Model at 868MHz for wireless sensor networks in outdoor scenarios," *International Workshop on Wireless Ad Hoc Networks (IWWAN 2005)*, London, May 2005.

[26] J. Lu, D. Lu and X. Huang, “Channel model for wireless sensor networks in forest scenario,” in *proc. IEEE Int. Conf. Informatics in Control, Automation and Robotics*, vol. 2, pp. 476-479, Apr. 2010.

[27] X. Deng and Y. Yang, “On-line adaptive compression in delay sensitive wireless sensor networks,” in *proc. IEEE Int. Conf. Mobile Adhoc and Sensor Systems*, pp. 452-461, Nov. 2010.

[28] Chipcon CC2420 radio transceiver datasheet, [Online]. Available: http://www.chipcon.com.

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