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Performance Modeling of Routing Dependability in Home Networks

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***Abstract*—In this paper, we propose a new routing protocol for home networks, called dependable routing protocol (DRP) that adapts to the changes in local topology within home networks environments. DRP is based on an effective selection of paths through which a packet must pass to reach the home unit. The selection, in such dynamic home networks, is made using dependable routing, i.e, in a way that maximizes the routes quality between the network nodes and the home unit while minimizing the Failure of Service (FoS). To minimize FoS, DRP maintains requirements on both the tolerable end-to-end delay (for time-sensitive routing) and the bit error rate (for reliable routing) within the network. To achieve this, we formulate the routing dependability problem mathematically as a constrained optimization problem. Specifically, analytical expressions for the route quality as well as the delay and bit error rate of a route in a home network scenario are derived. Numerical and simulation results show that the proposed approach gives optimal or near-optimal solutions and improves significantly the home network performance when compared to one prominent routing protocol: the Minimum Total Transmission Power Routing scheme, MTPR.**

I. Introduction

Wireless communications emerge as promising technologies to revolutionize our lives. Specifically wireless sensors are considered fundamental to establish the home network. Home network includes sensors attached to different systems [1], as shown in Fig. 1, including: the security and surveillance system (security cameras, fire alarms, and motion detectors), energy management system (home appliances, heat, ventilation and air conditioning), the outdoor systems (soil sensors, automatic spring system, and wind and rain sensors), the digital entertainment devices (laptops, TVs, home theater, cameras, printers ...) as well as the body area network [2]. The sensors, belonging to the different systems, send their data to a central control unit, which is the home unit (HU). The HU is responsible for forwarding these data to the interested parties, which could be the home owners, the utilities companies or others.

Home sensors have diverse real-time requirements since these sensors measure the physical status of dynamically changing environment. Some of the sensors report data periodically where they monitor a continuous real-time environment. Other sensors which detect a critical event create data at unpredictable times. We will call the periodic data and the unpredictable data the "sensory data".

Different sensory data has different delay threshold and reliability requirements depending on the sensed environment. For example, the temperature information in normal range can be delivered to the HU tolerating a higher threshold of delay and a certain percentage of loss compared to reporting very high temperature, which is an indication of fire. In summary, some nodes generate time sensitive data requiring urgent response, whereas others produce delay tolerant data. To achieve desired level of service for the users of the home network, it is necessary to ensure desired dependability i.e. reliability, availability, and maintainability for each type of data.

Due mainly to constraints on energy consumption in Wireless Sensor Networks (WSNs), where the sensors in home network operate on batteries, the design of routing protocols becomes different from the typical ad-hoc networks [3]. Thus, many energy-aware routing protocols has been proposed to extend the network life time [4], [5]. In view of this, the Minimum Total Transmission Power Routing scheme (MTPR) [4] tries to minimize the total transmission power for route connecting the source and destination nodes. Nevertheless, to cope with the dynamic home network system, we envision the establishment of routing dependability to be an important step. We argue that the routing protocol should consider other network parameters, in addition to energy consumption, such as the delay and error rate in order to provide consistent performance and behavior (dependable routing). Dependability modeling of wireless sensor networks is gaining popularity, since it helps to reduce risks of failure of service [6], [7]. Authors in [7] proposed an event-based middleware service which is designed for the application layer in WSNs, while our concern is specifically on the network layer in home networks. Thus, to the best of our knowledge, none of the existing routing protocols has considered routing dependability in such networks.

The remainder of this paper is organized as follows. Section II elaborates on the idea of dependability in home networks. Section III describes our proposed DRP protocol. In Section IV, we present the analytical framework used to evaluate the dependable routing problem. Numerical and simulation results are presented in Section V. Finally, Section VI contains our concluding remarks.

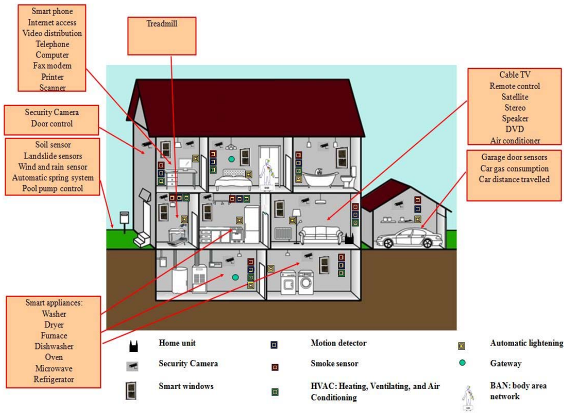

Fig. 1. System model for the home network

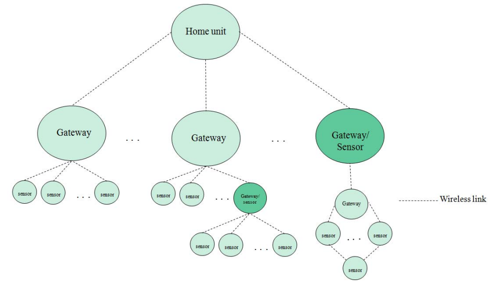

Fig. 2. Hierarchical structure of sensors in the home network

II. DEPENDABILITY

System dependability has been considered a fundamental quality that determines the system's ability to deliver continuous service to the end user [8], [9]. In the context of home networking, dependability refers to the ability of the dynamic and unpredictable wireless access systems to provide continuous services to the end users with minimum failure of service (FoS). Therefore, it is expected that a dependable home networking system will be functioning when needed (availability), the system will keep functioning correctly while being used (reliability), and it will be able to undergo modifications and repairs (maintainability) which results in minimum FoS . Thus, in this research, we mean by routing dependability: availability, reliability and maintainability of the routing service; our system should provide continuous routing service reducing the FoS.

Providing a dependable routing service for the sensory data in home networks that guarantees minimum failure of service is a challenging problem due to the following characteristics of home networks:

- Inherently unpredictable wireless channel characteristics due to the shared nature of the wireless medium, where there may be interference between the different devices (sensors and gateways).
- The nature of home networking services introduce many challenges for routing dependability including the following:
    1) Better service differentiation between the timely reporting of life-threatening conditions or rare events, and the transfer of continuous and periodic sensor data.
    2) Handling obstacles in homes such as walls and mobile objects that cause deterioration of the wireless link quality.
    3) Size and cost constraints on sensor nodes result in constraints mainly on energy which affects the sensor's lifetime [10] .

In the following section, we introduce our proposed Dependable Routing Protocol.

III. DEPENDABLE ROUTING PROTOCOL

First, in this section, we present the system model used to build our framework. Then, we present the functionality of our DRP protocol.

A. System Model

In this work, we consider a home network which consists of multi-purpose nodes (sensors/gateways) as shown in Fig. 2. These nodes generate heterogeneous traffic destined to the home unit (HU). Inside homes, these nodes generate various types of data which have various volumes and priorities. These nodes report three kinds of data: (T1) safety-critical data; (T2) data with economic value; and (T3) data for planning and management.

Sensory data usually flow from a distributed set of sensors to the HU. Since not every node is in the transmission range of the HU, it is the responsibility of the HU to decide on the multi-hop path followed by the messages sent from the different sensors through the intermediate nodes. Therefore, the route quality depends on the link qualities connecting the intermediate nodes along the path.

We envision a home network that consists of a number of sensors (nodes) which are connected with wireless links. We assume that each node has the ability to obtain its geographical position [1]. Also, each node knows the position and ID of its one hop neighbors by sending HELLO messages. If a node does not receive a HELLO messages from a neighbor during a certain time period then the link is considered down.

The home network is abstracted as a graph $G = (V, E)$, called a connectivity graph. Each node $v \in V$ represents a sensor node with a circular transmission range T_r. The neighborhood of v, denoted by $N_e(v)$, is the set of nodes residing in its transmission range. A bidirectional wireless link exists between v and every neighbor $u \in N_e(v)$ and is represented by an edge $(u, v) \in E$. The number of neighbors of a vertex v is called the connectivity degree of v.

B. Functionality of DRP

In DRP, a source node needs to know the route which it should use to forward data packets to the Home Unit. This information is provided by the Home Unit, which has an up-to-date view of the network topology. This HU acts also as a central controller where it is responsible for saving current information about all nodes in the home network. Specifically, each node reports its information to the HU at each pre-defined time interval containing the following details: the node ID, the time of the last update, the node location, the transmission range Tr, and the bit error rate (BER) as well as the link quality (LQ) of each link connecting the corresponding node

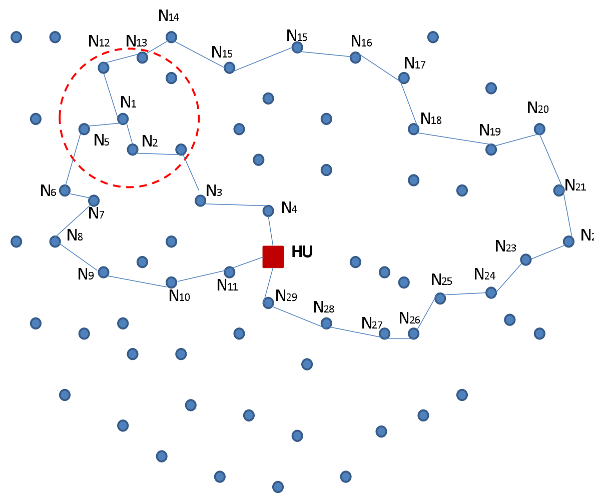

Fig. 3. Message routing in home networks

Algorithm 1 Dependable Routing Protocol

In the network
if (a home unit) **then**
  if Time to update **then**
    Receive the updated information from each node v_i in the home network;
    Recalculate the route y_i between each node v_i and the home unit;
    Send the information about the recalculated route y_i to node v_i;
  end if
end if
if (a node v_i) **then**
  Receive the updated information about route y_i;
  Save the updated route information;
  Use this route to forward the data packets to the home unit;
  Adjust (update) the transmission range Tr_i;
  calculate (update) the link quality $LQ_{i,j}$ to each neighboring node $v_i^j \in N_e(v_i)$;
  Send the updated detailed information to the home unit;
end if

to its neighbors (as will be shown in section IV). Based on this information, the HU constructs a set of routes between itself and all the network nodes.

To achieve routing *dependability*, the process of routes computation should ensure *reliability*, *maintainability* and *availability*. First, to ensure *reliability*, the constructed routes should be stable by guaranteeing a minimum FoS. To do so, DRP selects the path that has, with high probability, the most connected links. A connected link is the one with a maximum value of LQ. The selected path will be then sent to the corresponding network nodes and will be stored in the packets headers to allow the intermediate nodes to geographically forward packets. Note that, the path selection process is achieved while ensuring the QoS requirements, such as the tolerable end-to-end delay and the bit error rate constraints.

Second, to ensure both *maintainability* and *availability*, the constructed routes should be updated (maintained) according to the network topology (i.e., when the physical topology changes), notably in cases of sensors failure or when new sensors are added. Therefore, DRP needs to update the routing process in order to deal with the dynamic network environment. Mainly, in low density scenarios, one way to ensure both *maintainability* and *availability* is by increasing the connectivity probability which can be achieved by increasing the transmission range T_r of the nodes. On the other hand, when the network density increases, the Tr should be reduced to avoid high interference which reduces the bit error rate; but the Tr should still guarantee a high connectivity. Hence in DRP, the sensor nodes will decide on the transmission range that it should use in order to achieve high link connectivity and at the same time low bit error rate.

In summary, the dynamic network environment implies a variation in the communication traffic patterns, which DRP aims to mitigate. Variation in traffic patterns results in variation in information sent by the nodes. In this case, the HU will construct new routes that adapt to the changes in the information received from the nodes in the home network, which guarantee routing *maintainability* and ensures the routes *availability* under different network conditions.

To illustrate the functionality of DRP, let us consider the simple example presented in Fig. 3. Assume that sensor N_1 is added to the home network. To send its messages to the HU, there are many feasible routes such as: $N_1 - N_2 - N_3 - N_4 - HU$, or $N_1 - N_5 - N_6 - N_7 - N_8 - N_9 - N_{10} - N_{11} - HU$. For the first time, sensor N_1 use any of the feasible paths to send its information to the HU. When the HU receives this information, it calculates the optimal path and send it back to sensor N_1; which will be using this path for the future messages. More formally, Algorithm 1 illustrates the functionality of DRP.

In the following, we present the analytical framework which DRP uses to derive the route and link quality, end-to-end delay, as well as bit error rate.

IV. Analytical Framework

As stated before, we model the home network as a graph $G = (V, E)$ consisting of nodes (i.e., vertices) $v \in V$ and links $e \in E$ connecting these vertices. In the following, we derive analytical expressions for the link quality LQ of a link connecting the corresponding node v_i and its neighboring nodes $v_i^j \in N_e(v_i)$. Then we derive the analytical expression for both end-to-end delay and bit error rate of the route y_i in the home network which connects the node v_i to the home unit. The route y_i consists of a number of nodes $N_1, N_2, ..., N_m$ which are connected by a set of links $e_1, e_2, ..., e_n$; $m = n + 1$. Note that the node N_1 is the first node in the route, which is v_i and N_m is the last node in the route which is the home unit. Table I describes the parameters used in our analysis.

A. Link Quality LQ

Each node v_i needs to calculate the link quality $LQ_{i,j}$ for each link connecting it to the one hop neighboring nodes $v_i^j \in N_e(v_i)$. Recall that a node v_i^j is considered as a neighbor of the corresponding node v_i if $X_{i,j} \le T_{r_i}$, where $X_{i,j}$ is the distance

TABLE I
LIST OF PARAMETERS

Parameter	Description
D	delay of the route
RQ	route quality
LQ	link quality
P_c	connectivity probability
T_r	transmission range
E	energy level
D_{th}	thresholds on the end-to-end delay
BER_{th}	thresholds on the bit error rate
L	packet length
R_b	transmission data rate
m	number of nodes in one route
n	number of links in one route
N	number of nodes in the network
t_p	the time needed for a node to process and transmit a message

between v_i and v_i^j. To estimate $LQ_{i,j}$, v_i needs to calculate three components: the link's bit error rate $BER_{i,j}$, the link's connectivity probability $P_{c_{i,j}}$ and the energy efficiency of the neighboring node v_i^j.

In this work, we assume a Poisson node distribution within the network. The N nodes are distributed on a finite area A. The node spatial density ρ is defined as the number of nodes per unit area (i.e., $\rho = \frac{N}{A}$). Given a constant spatial density, the connectivity probability $P_{c_{i,j}}$ depends on the area covered by the transmission range T_{r_i}. Thus, the corresponding node needs to decide on T_{r_i} to guarantee that at least one node is within the transmission range. Hence, $P_{c_{i,j}}$ is calculated as:

$$P_{c_{i,j}} = 1 - e^{-\rho\pi T_{r_i}^2} \tag{1}$$

From equation (1), to increase the connectivity probability, the node needs to increase its transmission range. However, this results in increasing the interference with other nodes and then the bit error rate $BER_{i,j}$ (i.e., the second component in $LQ_{i,j}$). Hence, we modify the bit error rate given in [11] to become suitable for our case. $BER_{i,j}$ can be given as follows:

$$BER_{i,j} = Q(\sqrt{\frac{2\alpha_1 P_{t_i}/X_{i,j}^2}{P_{thermal} + E[P_{int}^{grid}]}}) \tag{2}$$

$$E[P_{int}^{grid}] = \frac{\alpha_1(1 - e^{\frac{-\lambda L}{R_b}})}{Tr_i^2} \sum_{j=1}^{s_i} P_{t_j} \frac{T_{r_i}^2}{X_{i,j}^2} \tag{3}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty exp(-\frac{u^2}{2})du$, $X_{i,j}$ is the distance between the two nodes v_i and $v_i^j \in N_e(v_i)$, s_i is the connectivity degree of the node v_i (i.e., $s_i = |N_e(v_i)|$), P_t is the transmission power, $E[P_{int}^{grid}]$ is the average interference power which depends on the number of neighboring nodes that transmit at the same time as the node v_i, and $P_{thermal} = \alpha_2 R_b$ is the thermal noise power (α_1 and α_2 are constants).

The third component needed to estimate $LQ_{i,j}$ is the remaining energy of the node $v_i^j \in N_e(v_i)$. Each sensor has an initial energy that is depleted as it receives and transmits packets. It is estimated that the ratio between the energy consumed in receiving and the energy consumed in transmitting a packet is 1.75. Thus, given that the energy needed to receive and transmit a packet of size L is $\frac{1.75P_{t_i}L}{R_b}$ and the current energy of a neighboring node $v_i^j \in N_e(v_i)$ is E_{c_j}, the energy efficiency $E_{i,j}$ of v_i^j is given as:

$$E_{i,j} = \frac{R_b}{1.75P_{t_i}L} E_{c_j} \tag{4}$$

Finally, the corresponding node v_i uses the following function to compute the link quality to its direct (single hop) neighbors.

$$LQ_{i,j} = w_1 \frac{P_{c_{i,j}}}{\sum_{j=1}^{s_i} P_{c_{i,j}}} + w_2 \frac{1}{\frac{BER_{i,j}}{\sum_{j=1}^{s_i} BER_{i,j}}} + w_3 \frac{E_{i,j}}{\sum_{j=1}^{s_i} E_{i,j}} \tag{5}$$

Where $w_i, (1 \le i \le 3)$ are weighting coefficients that could be used to set priority levels between the different components.

B. Minimum FoS requirements

To ensure the dependable routing service from a node v_i to the home unit, the latter needs to construct routes that meet the minimum FoS requirements, which correspond to the tolerable end-to-end delay and a threshold on the bit error rate.

The end-to-end delay $D(y_i)$ of a route y_i connecting the node v_i to the HU defines the time it takes for a packet to arrive at the HU from the time it was sent out from the corresponding node v_i. Route y_i consists of a total number of links n. Each link between two nodes on the route has t_p as a delay, where t_p is the time needed to process and transmit a packet [12]. Then $D(y_i)$ can be expressed as follows.

$$D(y_i) = \sum_{k=1}^{m-1} t_p \tag{6}$$

On the other hand, the bit error rate $BER(y_i)$ of a route y_i formed by n links is given by:

$$BER(y_i) = \prod_{k=1}^{m-1} BER_{k,k+1} \tag{7}$$

where $BER_{k,k+1}$ is given by the equation (2).

C. Formulating Message Routing as an Optimization Problem

We address now the problem of finding the optimal or near optimal route y_i, which is the route that maximizes the link qualities on the path, while satisfying the minimum FoS requirements. The HU uses an objective function to decide on the routes used by each node v_i to forward its packets. Note that the delay constraint is translated into an upper bound D_{th}, whose values depend on the intended home network applications. For instance, assigning low values for D_{th} corresponds to delay-sensitive applications. However, high values of D_{th} refer to delay-tolerant applications.

Hence, our approach can be formulated as an optimization problem with the objective function given as follows:

$$\max_{y_i \in A} \prod_{k=1}^{m-1} LQ_{k,k+1}(y_i) \tag{8}$$

For all nodes v_k in route y_i, this function is subject to the following constraints:

$$\begin{array}{ll} (a) & D(y_i) \le D_{th} \\ (b) & BER(y_i) \le BER_{th} \end{array}$$

TABLE II
PARAMETER SETTINGS

Parameter	Value	Parameter	Value
t_p	3 msec [12]	p_z	10
D_{th}	30 $\sim$ 150 ms (default 90)	μ	0.3
BER_{th}	1e-6 $\sim$ 1e-2 (default 1e-3)	θ	0.8
w_i $(1 \leq i \leq 3)$	$w_1 = w_2 = w_3 = \frac{1}{3}$	N_g	20

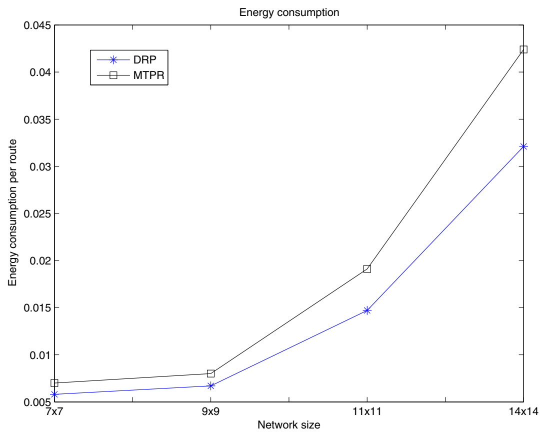

Fig. 4. Energy consumption in DRP and MTPR

Where A is the set containing all feasible routes from the node v_i to the home unit, and D_{th} and BER_{th} are thresholds on the tolerable end-to-end delay and bit error rate, respectively.

It is worth noting that the above problem is NP hard [13]. Hence to solve it, we propose a genetic algorithm, since this kind of heuristic methods yields better results for constrained routing problems [14] – [18]. However, due to space limitations, the details about our genetic algorithm are omitted.

V. Numerical and Simulation Results

In this section, we evaluate the performance of our proposal and compare it with respect to the Minimum Total Transmission Power Routing (MTPR) protocol. To this end, we developed our own discrete-event simulator using Matlab.

In our experiments, we simulated a grid network consisting of 7×7, 9×9, 11×11 and 14×14 nodes. The transmission range for each node is calculated based on the current network settings. We ran the simulation for a period of time $t_s = 1000\ s$. Additional parameter settings in our experiments are listed in Table II, where N_g is the number of generations for our genetic algorithm, μ is the mutation rate, θ is the crossover rate and p_z is the population size.

Fig. 4 shows the average amount of consumed energy in the routing process from a randomly selected source to a randomly selected destination for both protocols when varying the number of nodes. We can see that DRP consumes less energy compared to MTPR even in the large network case (i.e., 14×14 nodes). This is because MTPR chooses the nodes on the routes that have the maximum remaining energy without taking into account neither the links connectivity nor the links bit error rate. In general, in MTPR, more nodes are involved in the routing process, which increases the end-to-end delay and at the same time creates unstable routes because of the increased BER. This causes errors in delivering the messages and then

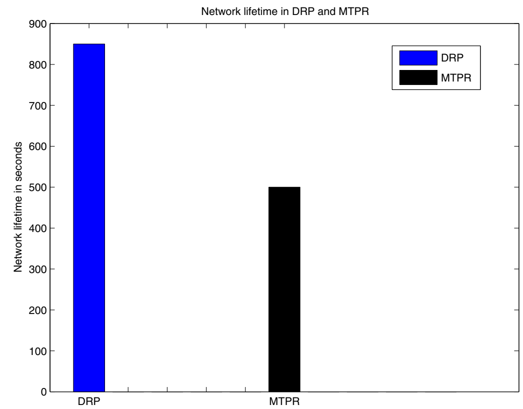

Fig. 5. Network lifetime in DRP and MTPR for the large network case

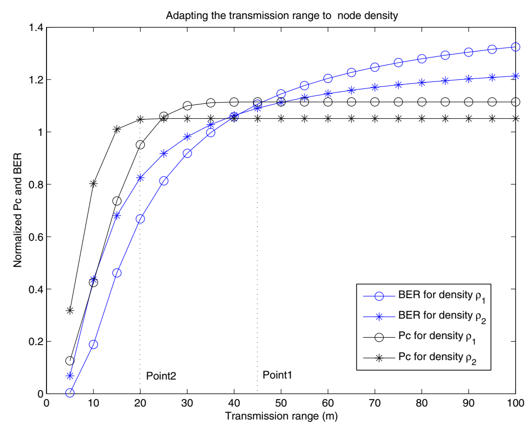

Fig. 6. Adapting the transmission range to the node density

more retransmissions will occur. As a result, more energy is consumed. On the other hand, DRP selects high quality routes satisfying higher connectivity, less bit error rate, less delay and less number of nodes. This minimizes the number of retransmissions and conserves the nodes' energy in the network.

Therefore, compared to DRP, MTPR consumes more energy causing the nodes to die faster as shown in Fig. 5, which depicts the network lifetime in the large network case. Recall that this metric is defined as the time needed for the first node in the network to die. We can see that the gain of DRP over MTPR can attain 70% in this case.

Let us now focus on the performance of our proposal. As stated earlier, each node decides on its transmission range that maximizes the connectivity probability and at the same time minimizes the bit error rate. Fig. 6 shows the effect of increasing T_r on both the connectivity probability and bit error rate for different node density values. As we can see, for low node density ($\rho_1 = 0.05\ nodes/m^2$), T_r is selected to be the point of intersection between the two curves, as indicated by point 1 in Fig. 6. As the node density increases ($\rho_2 = 0.3\ nodes/m^2$), the connectivity probability reaches 1 at low T_r values before its curve intersect with the bit error rate curve. In this case, in our simulations, T_r is selected to be the value which results in connectivity 1 and at the same time results in the lowest bit error rate, such as point 2 in Fig. 6.

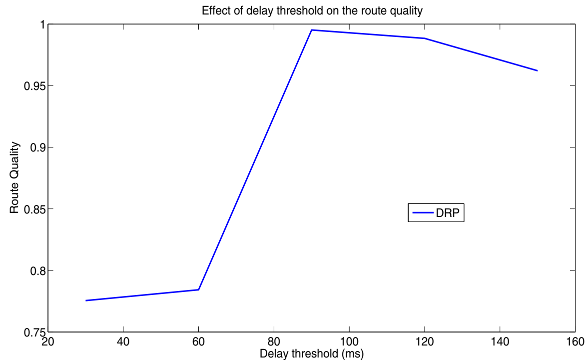

Fig. 7. Effect of end-to-end delay threshold on the route quality

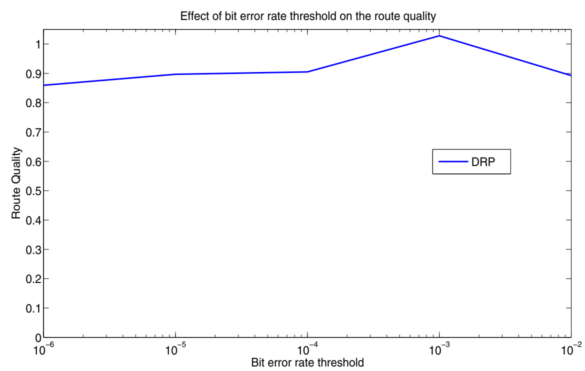

Fig. 8. Effect of bit error rate threshold on the route quality

Figs. 7 and 8 show the impact of end-to-end delay and bit error rate thresholds on the route quality selected by DRP, respectively. From Fig. 7, we can see that the route quality increases with the increase in delay threshold, but then begins to decrease if we increase further this parameter. This is due to the fact that, when we first increase the delay threshold, nodes with large number of neighbors can be selected which increases the link connectivity and then the link quality. Since the selected route is constructed from links with high quality and at the same time satisfying the minimum FoS requirements (i.e., the thresholds on both bit error rate and end-to-end delay), the route quality also increases as we increase the delay threshold. However, increasing the delay threshold further causes the route quality to deteriorate due to the increase in the contention in the selected routes. Hence, for delay sensitive applications, one should expect to specify the delay threshold as the minimum value that maximizes the route quality (in our case, $D_{th} = 90\ ms$).

Similar observations can be made when exploring Fig. 8. Indeed, increasing the bit error rate threshold allows the selected routes to have more and more nodes which causes contention in the network but at the same time increases the probability of connectivity of these selected routes. As such, the route quality improves. However, increasing further the bit error rate causes deterioration in the link quality due to the contention in the network. Hence, the bit error rate threshold can be selected as the one that maximizes the route quality (in our case, $BER_{th} = 10^{-3}$).

VI. Conclusion

Translating the routing dependability (i.e., reliability, availability and maintainability) into an acceptable level of Failure of Service (FoS) for the users in home networks is the key objective of our work. A network is only dependable when the required level of FoS can be achieved consistently or with enough high probability. In this work, we propose a new approach, called DRP, to optimize the network performance where we formulate the routing problem as an optimization problem. We compared our proposal with one of prominent protocols: MTPR. We found that DRP achieves better performance in terms of energy consumption and network lifetime. Indeed, the gain can attain 70% in large networks (i.e., 14×14 nodes). This makes our proposal a promising candidate for home networks.

References

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A Survey on Sensor Networks," IEEE Communications Magazine, 40(8):102116, 2002.

[2] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao, V. Leung, "Body Area Networks: A Survey", Mobile Network Application, 2010.

[3] C. Pandana and K. Liu, "Robust Connectivity-Aware Energy-Efficient Routing for Wireless Sensor Networks,", IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 7, NO. 10, 2008.

[4] C. Toh, "Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks," IEEE Communication Magazine , vol. 39, 2001.

[5] J. Chang and L. Tassiulas, "Maximum lifetime routing in wireless sensor networks," IEEE/ACM Trans. Networking, vol. 12, no. 4, 2004.

[6] M. Cinque1, D. Cotroneo1, C. Martinio1, S. Russo1, "Modeling and Assessing the Dependability ofWireless Sensor Networks," IEEE International Symposium on Reliable Distributed Systems, 2007.

[7] A. Taherkordi, M. Taleghan, and M. Sharifi, "Dependability Considerations in Wireless Sensor Networks Applications," Journal on Networks, Vol. 1, no. 6, 2006.

[8] D. Siewiorek, R. Chillarege, Z. Kalbarczyk, "Reflections on Industry Trends and Experimental Research in Dependability," IEEE Transactions on Dependable and Secure Computing, vol. 1, no. 2, 2004.

[9] A. Avizienis, J. Laprie, and B. Randell, "Fundamental Concepts of Dependability", research report N01145, Laboratory for Analysis and Architecture of System of the Nat'l Center for Scientific Research (LAAS-CNRS), 2001.

[10] H. Zhang, L. Sang, A. Arora, "Comparison of Data-Driven Link Estimation Methods in Low-Power Wireless Networks," IEEE TRANSACTIONS ON MOBILE COMPUTING, VOL. 9, NO. 11, 2010.

[11] S. Panichpapiboon, G. Ferrari, and O. Tonguz, "Optimal Transmit Power in Wireless Sensor Networks," IEEE TRANSACTIONS ON MOBILE COMPUTING, VOL. 5, NO. 10, 2006.

[12] S. Haykin and M. Moher, "Modern wireless communication," Prentice Hall, 2005.

[13] Z. Wang, J. Crowcroft, "Quality-of-Service Routing for Supporting Multimedia Applications", IEEE Journal on Selected Areas in Communications 14(7): 1228-1234 (1996).

[14] X. Cheng, "Multiple Description Video Communications in Wireless Ad Hoc Networks", master thesis, 2005.

[15] W. Mann and G. Smith, "A Comparison of Heuristics for Telecommunications Traffic Routing", In Rayward-Smith et al. (editors), Modern Heuristic Search Methods. John Wiley & Sons, 1996.

[16] J. Schaffer and L. Eschelman, "Combinatorial Optimization by Genetic Algorithms: The Value of the Genotype/Phenotype Distinction", In Rayward-Smith et al. (editors), Modern Heuristic Search Methods. John Wiley & Sons, 1996.

[17] D. Goldberg, "Genetic algorithms in search, optimization, and machine learning", Addison-Wesley, 1989.

[18] J. M. G. Lopez, M. Imine and O. B. Madsen, "Network Planning Using GA For Regular Topologies", In Proc. IEEE ICC 2008.