Energy Efficient Cognitive Unicast Routing for Wireless Sensor Networks

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***Abstract*—Survivability is crucial in Wireless Sensor Networks (WSNs) especially when they are used for monitoring and tracking applications with limited available resources. In this paper we are proposing the use of an energy Efficient Cognitive Unicast Routing (ECUR) protocol that tries to keep a balance between the energy consumption and the packet delay in a WSN. The proposed routing protocol has a next node selection criterion to change the routing path dynamically following the network conditions and the channel availability while the energy consumption per node is also considered. Simulation results are presented that show an increase in network lifetime of up to 30% compared with geographic opportunistic routing while the packet delay remains similar.**

I. INTRODUCTION

During the last decade, there has been a lot of interest in building and deploying Wireless Sensor Networks (WSNs). There is a plethora of applications such as event monitoring and tracking, where low-cost and easily deployed WSNs is the ideal solution. Inch scale sensor devices have been designed to work unattended with limited power requirements, for long periods of time. Compared to portable devices, such as cellular phones and laptops, where batteries can be recharged frequently, sensor node battery recharging or replacement is sometimes infeasible or impossible. The lifetime of any individual node, and as a consequence, of the whole network, is decided by how the limited amount of energy is utilized.

On the other hand, the packet delay is crucial to the success of these ubiquitous networks, especially in monitoring application. Network should provide high performance in terms of factors such as packet delay with a network resource optimization plan. Trying to network a large number of low-cost and low power sensor nodes is a challenging problem. Routing and addressing are the primary issues to be tackled at the network layer. In this work, we will focus on the routing problem and especially on dynamic routing with use of cognitive networking.

Crucial to the succeed of the protocol is the location information of each sensor node. The idea of dynamic routing according to location information was first introduced in [1]. In *Geographic Random Forwarding, (GeRaF)*, each packet carries the location of the sender and the destination and the prioritization of the candidates nodes is based on location information. This technique is simple to be implemented but it does not have any energy constrain. In [2], the impact of different selection criterion on the performance of a location based dynamic routing was examined. A *Real-time Opportunistic Routing Protocol, (ORTR)* was introduced in [3]. In this approach, the transmission power can be adjusted to follow the delay constrains. However, when a low duty cycle is applied, the forwarded area may not contain any nodes. An *Energy-Aware Real-Time Opportunistic Routing, (EARTOR)* is proposed in [4]. EAORTOR tries to maximize the number of requests realized when dealing with sequence of requests. The main restriction is that the requests should arrived one by one. The performance of opportunistic wireless communication in an indoor environment with a $3D$-ray tracing channel model have been studied in [5]. In [6–8] experimental evaluation and analysis are presented. A number of routing protocols for Cognitive Radio (CR) networks have been proposed in the literature. In [9] a joint interaction between on-demand routing and spectrum scheduling is proposed while in [10], a *Routing and dynamic Spectrum Allocation (ROSA)* algorithm is introduced. However, these approaches are not considering the energy efficiency.

An energy *Efficient Cognitive Unicast Routing (ECUR)* protocol is proposed in this paper in order to fill the gaps between the cognitive routing and energy efficient dynamic routing. *ECUR* tries to combine the packet delay that can be delivered from a cognitive network with the energy efficiency that can be guaranteed from an energy aware opportunistic routing protocol, [11]. The protocol ensures that the network connectivity is maintained, the energy consumption of each sensor node in the network is at a similar level and the network performance in terms of throughput and latency is guaranteed. In contrast with simple location based dynamic routing protocols, *ECUR* combines location and energy information to choose the next relay node.

The rest of this paper is organized as follows: System model is described in Section II while the proposed energy *Efficient Cognitive Unicast Routing (ECUR)* protocol is introduced in Section III, followed by the performance evaluation and simulation results in Section IV. Conclusion is in Section V.

II. SYSTEM MODEL

In this section, an overview of the basic functionality of the system model is provided.

A. Network address mechanism

Each sensor node should have a unique network address. Since the proposed protocol is based on location information about the nodes, the network address mechanism is related to

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the distance between a node and the destination. When the network address of node i is given and the network address of the destination node d is known, a delivery criterion $c_{i,d}$ should be locally obtained. This delivery criterion is correlated with the distance between the two nodes.

During an initialization phase, destination node broadcasts a number of identity advertisements packets. On the reception of a packet, a node calculates the number of the hops toward the destination, through different paths, and uses this number as the delivery criterion. Then, it floods the packet to its neighbor nodes. Finally, every node in the network has a delivery criterion through different paths toward the destination.

B. Radio implementation

Cognitive radio was first introduced in [12] as an ideal-omnipotent radio for user centric communications because it takes into consideration all the available parameters. For large-scale wireless network, two propositions were further suggested in [13]:

i) In order to avoid collisions with other simultaneous on-going transmissions, the radio can sense the spectrum resource, opportunistically, before any transmission.
ii) The radio can extract useful information for local cooperation by opportunistically polling one or more proximity radios onto the selected spectrum.

With the above proportions, we can extend the concept of cognitive radio to the area of cognitive network, which implements both dynamic spectrum and radio access.

C. Link model

There are three major factors that can affect the successful transmission of a packet between any two nodes:

i) *Channel availability.* In a link between two neighbor nodes there is a number of available channels N. When a node has a packet to transmit, it will sense for the available channel between all these N channels. If all the channels are occupied, the node has to wait for the next available channel. The number of the channels N should be carefully selected. A high number of channel may not be useful while it can lead the nodes to spend time and energy on sensing all the channels.
ii) *Channel access priority.* When a channel is free, a number of neighboring nodes that have packets to transmit will compete for that channel. When a node is transmitting over a channel, none of the nodes in its transmission range can use it. As a consequence, the priority criterion is crucial. In this work, the distance from the destination was used as a priority criterion. The node that is closest to the destination, according to its network address, will have the highest priority to access the next available channel.
iii) *Packet reception ratio.* When a node sends a packet to a neighbor node over a link there is a Packet Reception Ratio (PRR). To simulate a realistic channel model for lossy WSNs with Binary phase-shift keying (BPSK) without channel coding, the log-normal shadowing path loss model derived in [14], was used:

$$PRR(L_f, d) = (1 - \frac{1}{2}\exp^{-\frac{\gamma(d)}{2\times 0.64}})^{8\rho L_f} \quad (1)$$

where L_f is the length of the frame, d is the distance between the transmitter and the receiver, $\gamma(d)$ is the Signal to Noise Ratio(SNR) and ρ is the encoding ratio.

In each time slot, there can be one packet transmission over each available channel. When a packet is lost or damaged, it will be retransmitted in the next available time slot, following the routing protocol.

D. Collision avoidance mechanism

We make use of the cognitive radio to prevent collisions. The radio can have access to a group of data channels. Each group is associated with two different frequency tones, one for sensing and one for polling which are also distinctive from the data channel frequency. Therefore, the radio hardware should be composed of two transceivers, one for sensing/polling and one for data.

Initially, when a node has to transmit a packet, it senses for an available channel and then broadcasts a polling tone. All the nodes which are in the range of the transmitter node, they can detect this polling tone. A neighbor node can decide to join the transmission based on its own autonomous availability. If a node decides to join the transmission it sends out a polling tone to its surrounding nodes. In this way, sensing and polling tones protect wireless link module from spectrum interference.

E. Energy model

The energy model that is used is important for the proposed protocol. The packet transmission process is closely connected with the energy metric and as a consequence the routing paths are also affected. Depending on the metric, the characteristics of the protocol can change substantially.

The energy consumption is obtained by multiplying the power consumption and the packet transmission time. Each sensor node has an initial energy equals to E_{init}. The transmitting/receiving power is equals to P_{TX} and P_{RX} respectively, while the node also consumes energy on scanning the different channels, , P_{scan}, in order to check if there taking place any packet transmission. Every node consumes also power when it is on the idle/sleep mode, $P_{idle/sleep}$. The total energy consumption of a sensor node up to time t is equal to:

$$E_{cons}(t) = a\times P_{TX} + b\times P_{scan} + c\times P_{idle/sleep} + d\times P_{RX} \quad (2)$$

where a, b, c is the total transmission/reception time, scanning time and idle/sleep time respectively. The energy consumption during processing and queuing is also included in the b time. When E_{cons} is equal to E_{init} the sensor node runs out of energy and stops participate in any transmission.

III. ENERGY EFFICIENT COGNITIVE UNICAST ROUTING

The proposed energy *Efficient Cognitive Unicast Routing, (ECUR)* is a *reactive* routing protocol because it discovers routes only when desired. An explicit route discovery process is taken place only when is needed. In the introduced protocol, that process is *destination-initiated*. The destination node of the network begins the route discovery process and the process ends, when a routing path has been established while a maintenance procedure preserves it until the path is no longer available or desired.

In *ECUR*, multiple paths between the source and the destination are maintained. Packets can follow any of those paths, according to the dynamic changes of the network conditions, such as interference, channel and relay node availability, as well as the energy levels of the relay node. Moreover, due to the probabilistic choice of the relay nodes, the protocol is able to evaluate different routing paths continuously and choose them according to the condition in every time slot.

The proposed protocol has the following three phases:

I) *Initialization phase.* The destination node creates a small packet in order to transmit it toward the source node. That packet has the delivery criterion field, $c_{dst,dst}$ equals to zero. Every sensor node i in the network knows its relative location, hence it can categorize the nodes around it into *neighbor node set* and *candidate node set*. Neighbor node set of node i is a set S_i of all the nodes in the transmission range of node i:

$$S_i = \{j \in N | d_{i,j} \leq R\}, i \neq j \tag{3}$$

where N is the set of all the nodes in the network, $d_{i,j}$ is the distance between node i and node j and R is the transmission range of the node. Candidate node set of node i is a set V_i of those nodes that are closer to the *destination node of the packet*, than the transmitting node. Candidate node set is a subset of neighbor node set, $V_i \leq S_i$. During the initialization phase, the destination node of the packet is the source node s, hence:

$$V_i = \{j \in S_i | d_{j,s} \leq d_{i,s}\}, i \neq j \tag{4}$$

The destination node initiates the connection by flooding the packet to its candidate node set toward the source node. Every intermediate node forwards the packet to its candidate node set, while increasing the delivery criterion field.

On the reception of the packet, each node computes the power required for the transmission, P_{TX}. For instance, node A transmits a packet to node B. Node B will then flood the packet to its candidate node set while it will be able to calculate the energy for the transmission toward node A, as $E_{TX_{(B,A)}}$. In this way, the packet is moving from the destination to the source, with each node counting the delivery cost toward the destination. At the same time it calculates the energy metric for each transmission toward the destination.

When the packet reaches the source node, the source node calculates the delivery cost to the destination through different routes, estimates the energy required for transmission to the nodes at its candidate set and then drops the packet. After the end of the whole process, each sensor node in the network has all the necessary information to start transmitting data.

II) *Packet transmission process.* Packet transmission begins right after the initialization phase. There are four types of packets: DATA, acknowledgement (ACK), Request To Send (RTS) and Clear To Send (CTS). Every packet transmission is subjected to the PRR, as in Eq.1.

Every node has an initial energy, E_{init}. When a node n has a packet to transmit, there is a RTS/CTS handshake between the transmitter and the nodes at its candidate set. The transmitter search for an available channel C_i, floods a RTS packet over that channel and waits till the first response. The transmitter will wait for the response at the same channel C_i. Depending on the network conditions and the distance between the transmitter and the candidate node, as in Eq.1, some of the nodes in the candidate set will receive the RTS.

On the reception of a RTS packet, node k will response with a CTS to node n, if it is available for immediate packet transmission and there is no other packets waiting to be transmitted. Before the transmission of the CTS packet, node k will wait for time:

$$T_{backoff} = \frac{E_{cons}}{E_{init}} + \frac{1}{d_{k,n}} + SIFS, k \neq n \tag{5}$$

where E_{cons} is the total energy consumption of the node up to the current time slot and can be calculated as in Eq.2, $d_{k,n}$ is the distance between node k and node n and $SIFS$ is the Short Interframe Space.

After that time, node k will check if channel C_i, is available in order to response with a CTS *over the same channel* as the RTS. If the channel is unavailable, it will wait. Since the CTS transmission is also subjected to the PRR, there might be some packet losses. On successful reception of a CTS packet, transmitter will forward the DATA packet to the node that replied first with a CTS and will ignore any the consequent CTS packets for the same DATA packet. The transmission will take place *over the same channel* as the RTS/CTS handshake and the transmitter will wait for an ACK of the packet.

As it can be inferred from Eq.5, the selection criterion of the next relay node is a combination of the distance from the destination and the remaining energy at the node. During the initialization phase, each node calculates the transmission power required to transmit toward any candidate node. Hence, when a packet transmission is taking place every node can estimate the total energy up to that time.

Each intermediate node follows the same packet transmission process. Consequent packet transmissions might use different paths and different channels. This process continues till all the packets reach the destination node.

III) *Route maintenance.* Localized flooding is performed infrequently to keep all the information about the different routing paths updated. Sensor nodes that are not participating in any packet transmission at that time, helps with the collecting of the maintenance information. This process also helps to check if any new node joins the network or any other node run out of energy and stops operating.

IV. PERFORMANCE EVALUATION AND SIMULATION RESULTS

In this section, we compare the proposed protocol with geographic opportunistic routing in terms of total energy consumption, network life time and average end-to-end delay. The next relay node selection criterion in geographic opportunistic routing is the distance from the destination only, hence, in that approach, the first factor in Eq.5 is equal to zero.

The discrete event simulation system, OMNeT++ [15], was used for simulations. The sensor nodes were uniformly randomly distributed over a $100 \times 100(m^2)$ network field. The communication parameters were chosen based on IEEE 802.15.4. All the simulation parameters are listed in Table I.

TABLE I: Simulation Parameters

Parameter	Unit	Value
$Length\ of\ the\ data\ (L_f)$	*bit*	100×8
$RTS/CTS/ACK\ packet$	*bit*	8×8
$SIFS$	μs	10
$Transmission\ Range(R)$	m	10
$TransmittingPower\ (P_{TX})$	*mW*	15
$ReceivingPower\ (P_{RX})$	*mW*	10
$TransmissionRate$	*kbps*	250

A. Total Energy Consumption

The energy consumption is evaluated by simplifying the power consumption of the battery operated nodes. The sleeping mode power consumption is practically 1000 times smaller than P_{TX}, which is negligible for simulation purposes. The source node transmits 100 packets toward the destination node while the network density is increased.

The total energy consumption of the two approaches can be seen in Figure 1. In terms of total energy consumption for 100 packet transmissions, *ECUR* performs better than geographic opportunistic routing. This is mainly because of the cognitive aspect of the proposed protocol. In geographic opportunistic routing, every node has to wait for the channel to be available before transmitting. During that time, the node remain active and consumes energy. On the other hand, in *ECUR*, a number of different channels are used to forward the packets to the destination. Every node can select an available channel to forward the packet to an available candidate node. As a consequence, the time that the sensor nodes have to remain active in order to transmit a packet is smaller, leading a better total energy consumption.

As the number of the neighbor nodes increased, the number of the available paths also increased. Some of those paths can lead to the destination in less hops, leading both the protocols to decrease their total energy required. *ECUR* uses all these new path in a more energy efficient way and because of its cognitive aspect the difference between the two protocols increased as the number of the neighbor nodes increased.

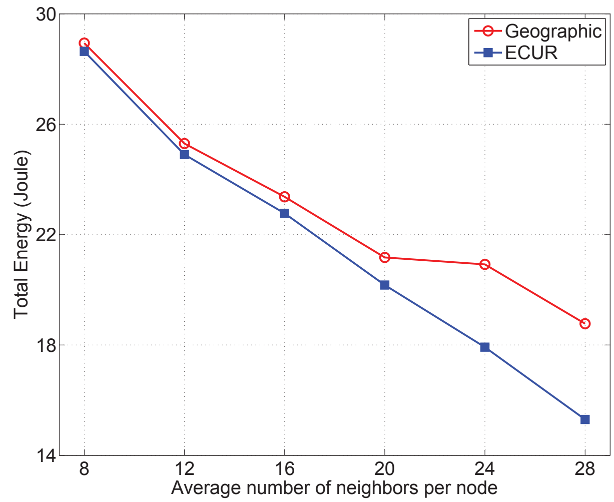

Fig. 1: Total energy consumption under different network density.

B. Network Lifetime

Network lifetime is defined as the interval between the beginning of a packet transmission of the network time until the first node failure due to battery depletion. Under the assumption that the sensor nodes operating on a pair of AA batteries with $1000mAh$ capacity, each sensor node will have an initial energy of:

$$\begin{aligned} E_{init}\ (J) &= capacity(Ah) \times voltage(V) \times time(s) \\ &= 1 \times 2 \times 1.5 \times (60 \times 60) = 10800J \end{aligned} \tag{6}$$

Figure 2 shows the results. The next node selection criterion in geographic opportunistic routing is the location of the nodes. When the network conditions remain stable, the same nodes are selected to forward the packets. Following this routing approach, these nodes will keep transmitting most of the packets and eventually they will run out of energy.

On the other hand, *ECUR* tries to discover paths that

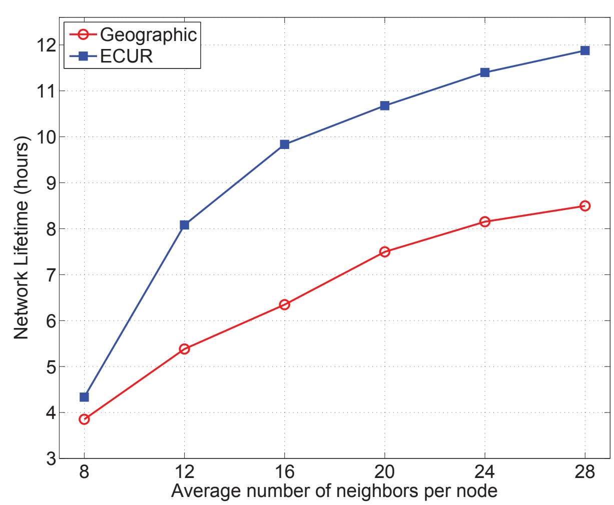

Fig. 2: Network lifetime under different network density.

consists of sensor nodes that are closer to the destination and also with the high energy levels, according to Eq.5. The location of the next node is important but the energy level of the next node is also crucial. Nodes that have not participated in many packet transmissions are preferred. As long as there are neighbor nodes in comparable distances with high energy levels, these nodes are preferred over nodes with lower energy levels. When all the nodes in a distance reach a similar low energy level, then the proposed protocol will use the remaining level of a node for a transmission and that node will run out of energy. In this way, network lifetime is higher than geographical routing. Moreover, as the network density increased there are more neighbor nodes in similar distances from the transmitter, extending the network lifetime.

C. End-to-end delay

End-to-end delay is the time required for a packet from the source to reach the destination. In our simulation a number of 1000 packets were transmitted from the source to the destination for each network density and the average end-to-end delay was calculated. The results are shown in Figure 3.

ECUR does not perform as well as geographic opportunistic routing when the network density is low. The main reason is that the cognitive aspect of that approach needs a sufficient number of neighbors in similar distances in order to perform as well as geographic routing. Without enough neighbor around, *ECUR* tends to use nodes with high energy levels, even if these nodes lead to paths with more hops, increasing the packet delay. As the network density increased, both the protocols performs better. More routing paths can be discovered, with less number of hops hence the packet delay is smaller. As the density increased *ECUR* starts having similar performance with geographic opportunistic routing. There are more neighbor nodes in similar distances that can deliver the packets at comparable times and *ECUR* uses these nodes.

V. CONCLUSION

In this paper, we are proposing an energy *Efficient Cognitive Routing*, *ECUR*, protocol for wireless sensor networks. The proposed protocol has a next relay node selection criterion that combines both location and energy information while it uses different channels. The protocol can deliver better results than geographical opportunistic routing in terms of energy consumption and extend the lifespan up to 30% while the packet delay remains similar.

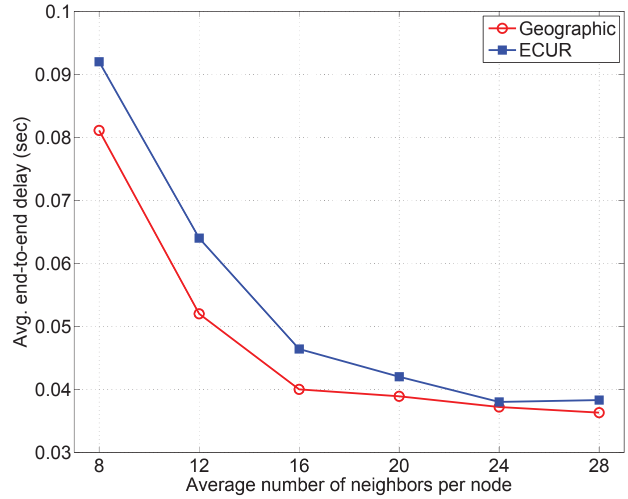

Fig. 3: Average end-to-end delay under different network density.

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