# Cognitive Networking with Opportunistic Routing in Wireless Sensor Networks

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***Abstract*—Under the cognitive networking architecture, this paper presents an opportunistic routing protocol for cognitive radio in Wireless Sensor Networks (WSNs), which can deliver higher performance and efficiency in multihop wireless communications. *Cognitive Networking with Opportunistic Routing, (CNOR)*, opportunistically routes traffic across paths over all available spectrum. A discrete event simulator is applied to evaluate and compare the proposed scheme against three other routing protocols: traditional routing with single channel, traditional routing with multiple channels and opportunistic routing with single channel. It is shown that by integrating opportunistic routing with cognitive radio much better results can be obtained, with respect to energy consumption, throughput and latency.**

## I. INTRODUCTION

Cognitive network is a networking system of cognitive radios that makes use of cutting-edge technology from computer networks to solve the problems in traditional wireless networks. Cognitive networking research is different from cognitive radio, as it covers all the layers of the OSI (Open System Interconnection) model, beyond layers 1 and 2 as with cognitive radio. One of the earlier attempts to define the concept of cognitive network was made in [1], where cognitive network is described as a network with a cognitive process that can perceive current network conditions, plan, decide, act on those conditions, learn from consequences of its actions, and follow end-to-end goals. This definition however did not explicitly describe what is the knowledge of the network. In [2], cognitive networking is viewed as a communication network augmented by a knowledge plane that can span vertically over layers and/or horizontally across technologies. The knowledge plan is composed of at least two elements: 1) a representation of relevant knowledge about the scope; 2) a cognition loop which has the intelligence inside its states.

The concept of cognitive network is further detailed in [3], where the cognitive networking concept is interpreted as a network that can utilize both radio spectrum and wireless station resources opportunistically, based upon the knowledge of such resource availability. Since cognitive radio has been developed as a radio transceiver that can utilize spectrum channels opportunistically (or Opportunistic Spectrum Access OSA), the cognitive network is therefore a network that can opportunistically organize cognitive radios.

In this paper, we further investigate multihop wireless communications in cognitive networks, under a Wireless Sensor Network (WSN) scenario. By the integration of opportunistic routing and opportunistic spectrum access, we show how the cognitive networking approach can improve the quality of wireless communications, as compared to the upper-bound of traditional wireless networks. We also study how the network energy consumption is impacted which can be especially important for WSNs, [4]. Network simulation results are explained with performance evaluation and analysis.

The rest of this paper is organized as follows: Related works are reviewed in Section II. Routing protocols are described in Section III followed by performance evaluation and simulations in Section IV. Conclusions are summarized in Section V.

## II. RELATED WORKS

Opportunistic routing has attracted much attention as it is considered a promising direction for improving the performance of wireless ad hoc and sensor networks [5]. It tries to take advantage of broadcast characteristics of wireless transmission. The path can change dynamically, following the network conditions, making it suitable for cognitive radio networks with fast variation of spectrum availability. The idea of opportunistic routing has been introduced in [6]. *Extremely Opportunistic Routing (ExOR)*, allows the routers to use multi-path routes toward the destination. Every link between a transmitter and a receiver has a priority level according to the *Expected Transmission count (ETX)* metric, [7], which is based on the distance between the receiver and the destination. The shortest the distance, the highest the priority. *MAC-independent Opportunistic Routing and Encoding Protocol (MORE)* [8] tries to enhance ExOR. MORE provides opportunistic routing by a network coding approach extended to multicast. It also uses the concept of innovative packets in order to avoid duplicate packets which might occur in ExOR.

A spectrum aware routing is proposed in [9]. *Spectrum Aware Mesh Routing (SAMER)*, opportunistically routes traffic across paths with higher spectrum availability and quality. SAMER tries to balance between long-term route stability and short-term opportunistic performance. In [10] a *Spectrum Aware Opportunistic Routing (SAOR)* algorithm is introduced. SAOR uses an *Opportunistic Link Transmission (OLT)* metric,

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which is a combination of transmission delay, packet queueing delay and link access delay. By introducing channel access probability to characterize the opportunistic CR link, *Multi-channel Spectrum Aware Opportunistic Routing (MSAOR)*, [11], improves the performance of SAOR in a three-node network.

In this paper, we propose an opportunistic routing protocol with opportunistic spectrum access for WSNs. A selection criterion is proposed, that has been designed by taking into consideration the limited energy resources and computational capabilities of sensor nodes. A simple network address mechanism is used in order to obtain the selection criterion. To make the link model more practical, a packet error rate has been assigned over each available link while a collision avoidance scheme that prevents collisions by making use of the cognitive radio is applied. The proposed scheme is evaluated through a large scale sensor network via a discrete event simulator and is compared with three other routing schemes.

## III. ROUTING PROTOCOLS

In this section, three routing protocols are briefly presented, followed by a description of the proposed opportunistic routing scheme for cognitive networking.

### A. Traditional Routing

Traditional routing starts with an initialization phase. Destination node broadcasts a number of packets and every node in the network keeps broadcasting these packets to its neighbor nodes. Each packet transmission over a channel is subjected to a *Packet Error Rate, (PER),* which can be calculated as in [12]. Some packets will be lost due to the $PER$ between the communicating nodes. After this phase, every node will know the $PER$ over the links with its neighbor nodes and the number of the hops that are needed to reach the destination through different paths and the related distances.

This approach is using only one channel. The source node will select the path toward the destination according to the distance from the destination and the link reliability. The selected path will be the shortest path toward the destination and consist of links with $PER$ less or equal to a predefined *reliability threshold*, $PER_{th}$. A link $i$ between a node and one of its neighbor nodes will be considered to be in the path only if $PER(i) \leq PER_{th}$. From those links the node will always forward the packet over the one that leads to the neighbor which is closer to the destination. All the packets will be delivered to the destination following the same path.

Traditional routing uses two types of packets: DATA and acknowledgment (ACK). When a node transmits a packet, it will store a copy in its buffer and will wait for the ACK. The time the node will wait for an ACK can be determined as:

$$T_{ACK} = TD_{DATA} + SIFS + (2 * T_{pd}) + TD_{ACK} \quad (1)$$

where $TD_{DATA}/TD_{ACK}$ is the transmission delay for DATA/ACK, $T_{pd}$ is the propagation delay, and Short Inter-frame Space (SIFS) is the small time interval between the DATA packet and its ACK.

If there is no ACK after that time, because the DATA or the ACK packet was lost, the node will retransmit the DATA packet. If two or more nodes transmit at the same time, there will be a collision and both packets will be dropped. To avoid that, there is a global scheduler that prioritize packet transmission. The node that is closer to the destination will transmit the packet first while the other nodes will go back to sleep mode. Global scheduler will wake up a node only when it can transmit packets. The use of global scheduler exclude retransmissions due to collisions and the performance results can be considered as an upper-bound of this routing protocol.

### B. Traditional Routing with N channels

Traditional routing with N channels (traditional cognitive radio) is similar to traditional routing. An initialization phase has to take place before starting the packet transmission and the process that will be followed to find the path to the destination is the same as in traditional routing.

Instead of one single channel, this protocol uses N channels. When a node has a packet to transmit, it will sense all the channels to find one available. If there is an available channel, it will transmit the DATA over that channel and will wait for the ACK. The receiver has to reply with an ACK *at the same channel*. In this way, transmitter will not sense all the channels for the ACK but only the one through which it sent the DATA. If there is no channel available the transmitter goes back to sleep mode. Global scheduler is also used in this protocol.

Assuming that node A transmits a packet to node B over channel $i$, while node B is transmitting a packet to another node C, over channel $j$, with $i \neq j$. In that case, node B will drop the packet from node A because it is trying to transmit a packet to node C. To cope with that problem, in every time slot, the global scheduler knows which of the neighbor nodes of the transmitter are available to receive a packet. If the neighbor node that should get the packet, following the routing protocol, is not available, the transmitter will remain in sleeping mode. The use of the global scheduler again in this approach helps to avoid any collisions. Every packet will have the best available scheduling and the results will be an upper-bound of this routing protocol.

### C. Opportunistic Routing

There are four types of packets: Request To Send (RTS), Clear To Send (CTS), DATA and ACK. Every packet transmission is subjected to PER, there is no global scheduler. There is only one channel in that approach.

When a node has a DATA packet to transmit, it stores the packet in a buffer and then broadcasts a RTS packet for that DATA packet to all the neighbor nodes. Transmitter will wait for a CTS packet for time $T_{RTS}$ equal to:

$$T_{RTS} = TD_{RTS_{MAX}} + SIFS + (2 * T_{pd}) + TD_{CTS_{MAX}} \quad (2)$$

where $TD_{RTS_{MAX}}/TD_{CTS_{MAX}}$ is the maximum transmission delay for RTS/CTS to reach a node placed at the limit of the transmission range of the transmitter. This is the smallest time interval the transmitter has to wait before assuming that the RTS or the corresponding CTS packet was lost, even from a neighbor node that is located at the transmission range limits. If there is no CTS after time $T_{RTS}$, the node will broadcast a RTS for the same packet again.

When a neighbor node, $n$, receives a RTS packet from the transmitter node $t$, it will reply with a CTS packet after time $T_{Backoff}$, equals to:

$$T_{Backoff} = \frac{C_0}{D_{t,d} - D_{n,d}} + SIFS, t \neq d \tag{3}$$

where $D(t,d)$ is the distance between the transmitter node $t$ and the destination node $d$ and $C_0$ is a constant. In order for a node to reply with a CTS before the transmitter broadcast the same RTS, from Eq.(2), $C_0$ should be smaller than SIFS, $C_0 \ll SIFS$.

Transmitter node will forward the DATA packet to the neighbor node that will reply first with a CTS packet. If there is no ACK after time $T_{ACK}$, Eq.(1), the node will transmit the DATA packet again.

$T_{Backoff}$ is inverse proportional to the difference $D(t,d) - D(n,d)$. The neighbor node that is closer to the destination will have the smallest $T_{Backoff}$ and will try to reply first with a CTS packet. Any CTS that will arrive to the transmitter after the first one, will be ignored. Any neighbor node that is still during its $T_{Backoff}$ and listen a DATA packet transmission, will drop the CTS packet and go back to sleep mode.

As it can be inferred from Eq.(3), the selection criterion of the proposed routing protocol is the distance between the node and the destination. That selection criterion is easy to be implemented in WSNs which have limited capabilities. Each sensor needs to know its own network address and the destination node network address to calculate the criterion.

In this approach, the routing path changes dynamically in every time slot according to the network conditions. Since there is no reliability threshold, this approach can follow paths toward the destination that needs less hops than traditional routing. Moreover, in every packet transmission the number of the successfully transmitted RTS and/or CTS packets is different, leading to different next relay nodes and different paths toward the destination.

### D. Cognitive Networking with Opportunistic Routing (CNOR)

CNOR, tries to combine the advantages of opportunistic routing and opportunistic spectrum access (traditional cognitive radio). The routing process is similar to the single channel opportunistic routing.

When a node has a packet to transmit, it senses for an available channel. If there is a channel available, it will broadcast a RTS over that channel. All the consequence packets, CTS, DATA and ACK, will be transmitted *over the same channel* as the RTS. This approach also follows the cognitive collision avoidance mechanism as in [13]. Moreover, since opportunistic routing can change the path dynamically following the network conditions, there is no need for a global scheduler. If node A transmits a RTS to node B over channel $i$, while node B is transmitting a packet to node C over channel $j$, with $i \neq j$, node B will just ignore the RTS. Another neighbor node that hears to that RTS will reply. As a consequence, in contrast to traditional routing with N channels, in *CNOR* the packets will make progress toward the destination in every time slot, with higher probability.

## IV. PERFORMANCE EVALUATION AND SIMULATION RESULTS

We utilize simulation tools to study the performance of the proposed schemes. In this section, the simulation parameters are described, followed by the performance metrics that were used and the simulation results.

### A. Simulation Parameters

A simulation model, using OMNeT++ [14], was implemented for our Cognitive Radio system model with the protocols described in the previous section.

The sensor nodes were uniformly randomly distributed over a $350 \times 350(m^2)$ network field. Every node has 6 neighbor nodes on average and transmission range 12 meters. The communication parameters were chosen based on IEEE 802.15.4, as listed in Table I.

TABLE I: Simulation Parameters

| Parameter | Unit | Value |
|---|---|---|
| $Wireless\ channel\ path\ loss\ compnent\ (n)$ | | 2.5 |
| $Constant\ decided\ by\ the\ antenna\ gain\ (A)$ | *dB* | $-31$ |
| $Noise\ Power\ (\sigma_n^2)$ | *dBm* | $-92$ |
| $SIFS$ | $\mu s$ | 10 |
| $DATA\ packet$ | *bit* | $119 \times 8$ |
| $RTS/CTS/ACK\ packet$ | *bit* | $8 \times 8$ |
| $C_0$ | | 1 |

The number of the channels was set to 3. A higher number of channels was also tried but the difference in performance was negligible while the algorithm complexity in each sensor node was increased. The nodes had to spend more time on sensing all the channels. When 2 channels were simulated, nodes spent less time on channel sensing but we didn't get full advantage of the cognitive radio concept because of the limited available channels.

For the traditional routing schemes, the reliability threshold was $20\%$. During the simulation, 9 different source-destination distances were selected, starting from $50m$ till $450m$ with $50m$ step. To explore the performance of the protocols in different locations of the network, in every distance, 4 different destination nodes were simulated with deviation $1m$ from the main distance. For instance, in $50m$ from the source, 4 destination nodes were selected in distance between 49 and 51 $meters$ from the source. For each source-destination pair, we ran the simulation 5 times, on average. The performance metrics that were used, are the average values per distance of all the 4 destinations. The network topology with the different destination nodes in each distance can be seen in Figure 1.

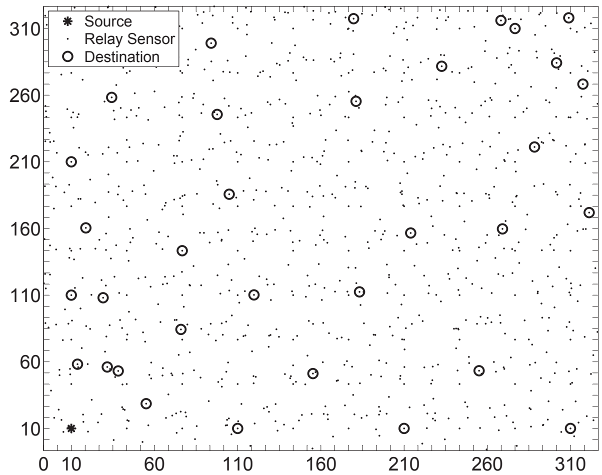


Fig. 1: Network topology with one source and 4 destinations in each distance.

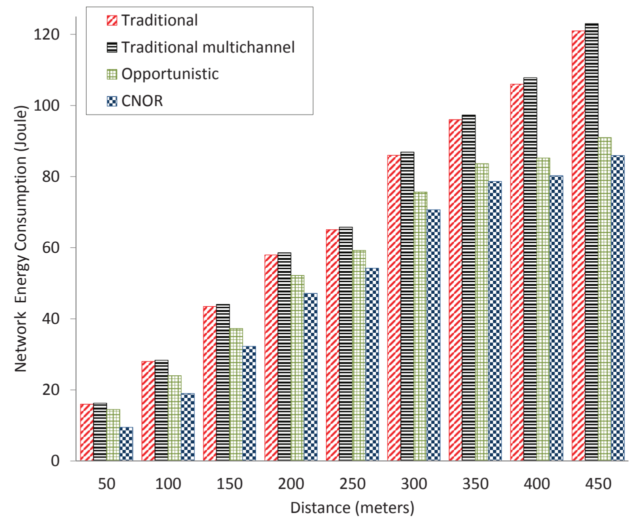


Fig. 2: Network energy consumption of the different schemes.

## B. Performance Metrics

The routing schemes compared with respect to energy consumption, throughput and average end-to-end delay.

*1) Energy Consumption:* Energy consumption is the total power needed from all the nodes in the network. The source node transmitted $100$ packets toward the destination.

Let the node power consumption in transmitting and receiving/idle modes be denoted by $P_{trans}$ and $P_r/i$ respectively. The sleeping mode power consumption is practically $1000$ times smaller than $P_{trans}$ and $P_r/i$, which is negligible. Let $P_{trans}$ = 15mW and $P_r/i$ = 10mW. For each distance, there are $4$ different destination nodes. The average energy consumption for each distance can be seen in Figure 2.

For traditional routing, an ideal sleeping mechanism was used. The nodes knew exactly when to sleep and when to wake up for a packet transmission. In most practical networks, the nodes will stay awake when there is traffic, and the network energy consumption will be approximately inversely proportional to the throughput. In our approach, with the ideal sleeping mechanism, which was used only in traditional routing, the upper bound of the performance of traditional routing was achieved.

Traditional routing with 3 channels consumes slightly more energy than the single channel. The two approaches are using the same path toward the destination and the same scheduler. However, when there are 3 channels available, the nodes have also to scan the different channels, consuming more energy. As the distance increased, the number of the hops also increase, more nodes are used and the difference in energy consumption between the two traditional approaches, increased.

Opportunistic routing performs better than traditional routing. The path between the source and the destination may consist of links with any $PER$. That can lead to shorter paths than the traditional routing path, with fewer hops and node transmissions, decreasing the total energy consumption. As the distance between the source and the destination is increased, there are more nodes in-between them, leading to even shorter paths toward the destination. As a consequence the difference between the energy consumption of traditional and opportunistic routing is increased. *CNOR* has the smaller energy consumption over all the other protocols. It can discover shorter paths than traditional routing while at the same time it has higher probability to transmit a packet in every time slot. Comparing with single channel opportunistic routing, in this approach, the packets can make progress toward the destination over multiple channels in every time slot. The time a node has to wait before transmitting a packet is smaller and as a result the energy consumption of each node is smaller.

*2) Throughput:* Throughput is the number of bits divided by the time needed to transport the bits. From the source node $100$ packets were transmitted toward the destination. The simulation parameters are listed in Table I. The average throughput for each distance can be seen in Figure 3.

Traditional routing with single channel has the lowest throughput over all the other protocols. As the distance between the source and the destination increased, the throughput decreased. There are more hops needed to deliver a packet to the destination, hence, the time needed is higher and the throughput is lower. Traditional routing with 3 channels performs better than the single channel. In one time slot, if one of the channels is occupied, a node can transmit a packet to a neighbor node over the any of the other two available channels. At a given time, more packets will be transmitted toward the destination, over different channels, than with single channel traditional routing. A problem with both these two approaches is that, if a packet is lost, all the sequential packet transmission will have to wait, because all the packets should be transmitted through the same nodes.

Opportunistic routing performs even better than traditional routing. The path between the source and the destination changes according to network conditions and node availability. Packets will be transmitted to different nodes in every time slot and paths with less hops than traditional routing will be discovered. The time needed to transport the bits will be

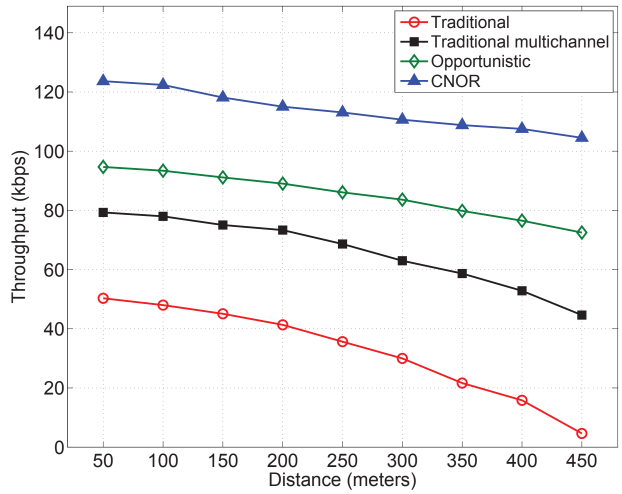


Fig. 3: Throughput of the different schemes.

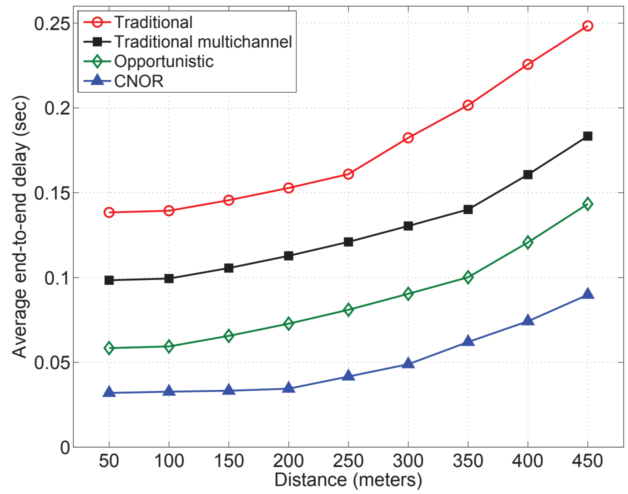


Fig. 4: Average end-to-end delay of the different schemes.

smaller and the throughput will be higher. *CNOR* has the best performance over all. In every time slot, packets can be transmitted through the shorter available path at the time, toward the destination, and over multiple channels. The time needed to transport the bits is smaller, than with single channel opportunistic, leading to a higher throughput.

*3) Average end-to-end delay:* Delay of a packet in the network is the time it takes the packet to reach the destination after leaving the source. The source node sends $100$ packets toward each destination, with a transmission time of $6.4ms$. The results can be seen in Figure 4.

Traditional routing with single and with 3 channels performs worse than opportunistic routing. The path that these protocols follows is the shortest available under the reliability threshold. Moreover, all the packets following the same path, hence, when a packet is lost or damaged, all the sequential packets will be delayed. Traditional routing with 3 channels performs better that traditional routing with single channel, the probability of a packet to be transmitted at a time slot is higher. The packet can be transmitted over any of the 3 channels, if any is available. Hence, the time needed for a packet to reach the destination s smaller.

Opportunistic routing can discover shorter paths towards the destination than traditional routing. Each packet need less time to reach the destination, leading to smaller packet delay. As there are more channels available, in *CNOR*, that time is even smaller.

## V. CONCLUSION

Cognitive radios networks hold promise in significantly increasing radio spectrum utilization through dynamic spectrum sensing and opportunistic utilization. In this paper, we proposed a *Cognitive Networking with Opportunistic Routing,(CNOR)*. The routing metric of the proposed scheme is the distance from the destination. It is compared with traditional schemes with single and multiple channels as well as with opportunistic scheme with single channel. Simulation evaluations have shown that the proposed scheme is a viable routing solution and can provide better performance than the other schemes in WSNs.

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