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A NOVEL JOINT CHANNEL ASSIGNMENT SCHEME FOR COGNITIVE RADIO WIRELESS SENSOR NETWORKS

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Abstract. *Multi-hop transmissions over a single channel that is shared by all the nodes in a network limit the throughput of conventional multi-hop wireless sensor networks. To improve the performance of these networks, the use of multiple channels has been proposed. Channel assignment is an important problem in multi-channel wireless sensor networks; it asks the question of how channels should be assigned so that the network performance is maximized. Many existing channel assignment schemes seek to improve network performance by trying to reduce interference. However, it is not easy to measure the actual amount of interference in a network. We addressed the channel assignment problem from a novel approach. Instead of distributing the nodes, links or network interfaces to different channels to reduce interference, we try to assign as many channels as possible to the links. A new distributed scheme is proposed and we show that it outperforms comparable schemes.*

Keywords: Channel assignment, Cognitive radio wireless sensor networks, Distributed method

1. **Introduction.** Nodes communicate with each other using a shared channel in conventional multi-hop wireless networks such as a wireless sensor network (WSN). Due to the multi-hop transmissions and the use of a shared channel, more contention and interference result in such a network which leads to throughput reduction when compared to an equivalent infrastructured counterpart. Using multiple channels within a network can alleviate the throughput problem in conventional WSNs. Meanwhile, the use of the radio spectrum is regulated by certain authoritative bodies. This fixed spectrum assignment policy has led to the problem of uneven spectrum usage where low utilization is observed in certain licensed bands while the unlicensed bands are becoming increasingly congested. To overcome this, the cognitive radio (CR) paradigm [1] allows unlicensed users to use the licensed bands in a non-intrusive manner. A network formed by a group of unlicensed users constitutes a cognitive radio ad hoc network (CRAHN). CRAHNs are similar to multi-channel WSNs in many ways, both are multi-hop wireless networks and both use multiple channels. From the viewpoint of network algorithm design, the difference between them lies only in the availability of the channels [2]. Many existing channel assignment schemes seek to improve network performance by trying to reduce interference. In this paper, we propose a joint channel assignment scheme for cognitive radio WSNs. We show that not only is the actual amount of interference difficult to be measured, but attempting to minimize interference by distributing the nodes, links or network interfaces to different channels does not necessary yield the largest gain in network performance. We addressed the channel assignment problem from a novel approach.

Instead of distributing the nodes, links or network interfaces to different channels, we try to assign as many channels as possible to the links. Through NS-2 based simulation, we found that the proposed scheme outperforms other protocols on network throughput.

The remainder of this paper is organized as follows. We give the details of the proposed scheme in Section 2. In Section 3, we investigate the feasibility of the proposal. Finally, we conclude in Section 4.

2. System Model and Problem Formulation.

2.1. System architecture and models.

In this paper, we assumed that unlicensed users operate on both unlicensed and licensed channels. There is only one unlicensed channel in a network and it is used as the common control channel for the network. An unlicensed user is assumed to be equipped with $n_i \geq 1$ network interfaces and there are a total of $n_c \geq 1$ channels (unlicensed plus licensed) in a network. An unlicensed user dedicates one of its n_i network interfaces as the control network interface which is tuned to the common control channel permanently. For ease of exposition, the other network interfaces are henceforth called the non-default network interfaces.

A network is modeled as an undirected graph called the connectivity graph $G_c(V_c, E_c)$, where V_c is the set of unlicensed users in the network and E_c is the set of links in the networks. A link $l_{i,j}$ is in E_c if the Euclidean distance between nodes i and j, $r_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \leq R$ where (x_i, x_j) is the coordinate of node i in the two-dimension Cartesian plane and R is the maximum node transmission range. The conflict graph is often used to quantify the amount of interference in channel assignment schemes. Given the connectivity graph of a network $G_c(V_c, E_c)$, the conflict graph is given by $G_{cf}(V_{cf}, E_{cf})$, where V_{cf} corresponds to the links in G_c, and two vertices $v1_{cf}, v2_{cf} \in V_{cf}$ have an edge between them if the links that they represent in G_c interfere with each other and cannot be activated simultaneously.

Licensed user activity is modeled according to the two-state ON/OFF process [3]. A licensed user cycles between the two states beginning with an OFF state. A licensed user stays in an OFF state for T_{off} seconds and occupies a licensed channel randomly (uniform probability) in an ON state for T_{on} seconds at a random location. Both T_{off} and T_{on} are assumed to be exponentially distributed. While in an ON state, a licensed user is assumed to be motionless.

2.2. Joint channel assignment scheme.

2.2.1. *Insufficiency of using the conflict graph to quantify interference.*

Many channel assignment schemes quantify interference using the method of conflict graph instead which measures the potential/maximum interference and not the actual interference. To grasp this idea, let us consider the network in Figure 1(a). Suppose that the nodes each has only one network interface and all the links in the network are assigned to the same channel. The corresponding conflict graph for the network is given in Figure 1(b). According to the conflict graph, the amount of interference in the network is six (six edges). However, some links are not used when network traffic and routing are taken into account. For example, suppose a traffic flow flows from node 1 to 2 taking the path 1-0-2. In this scenario, we observed that links (0-3) and (0-4) are not used. As they are not used, they do not interfere with other links which implies that the actual/true network interference is less than six.

2.2.2. *The proposed scheme for assigning more channels to a link.*

Assigning more channels to a link has many benefits. One of the benefits is that the link's aggregate capacity can be improved. For example, if the capacity of a channel is 100kB/s, a path f_1 with 150kB/s cannot be supported by the network in Figure 2(a) in which each link consists

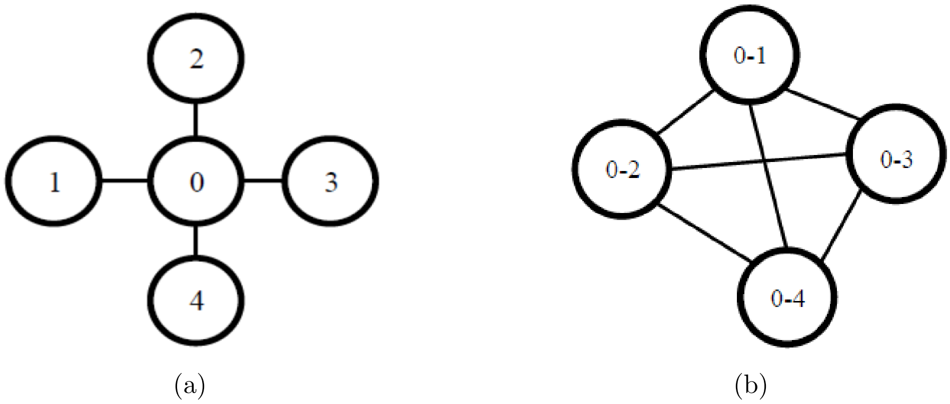

Figure 1. (a) A network where all the links are assigned to the same channel; (b) the conflict graph for the network

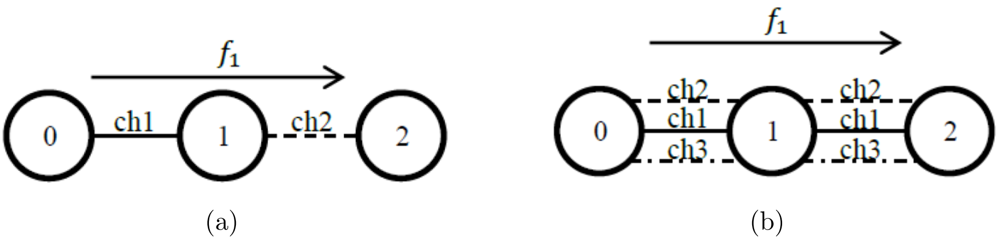

Figure 2. (a) Links are assigned to different channels; (b) links are assigned to the same set of channels.

of only one channel and both links are assigned to different channels in order to reduce interference. On the contrary, there is no such problem with the network in Figure 2(b) in which each link consists of three channels.

A link made up of more channels is also more stable [4]. A link is broken if the channels assigned to it suddenly become unavailable due to the arrival of licensed users. If unlicensed users use only licensed channels, when a link is assigned only one licensed channel and the channel suddenly becomes unavailable, a route repair or new route discovery is required. Route repairs or route discoveries usually involve duplicating and flooding of RREQs which increases channel contention and interference (broadcast storm problem [5]). When more channels are assigned to a link, the link can be used on other channels when one of the channels assigned to it suddenly becomes unavailable.

2.2.3. *A new channel metric: Neighbor Affinity Score (NAS).* The channel assignment process in CR-EAOMDV is based on the "propose-and-follow" concept. A new channel metric to facilitate channel selection at nodes called Neighbor Affinity Score (NAS) is proposed and its equation is given in Equation (1). When used in conjunction with a distributed protocol, what NAS tries to do is "coerce/encourage" nodes to assign channels to their network interfaces in such a way that more channels are assigned to the more heavily utilized links in the network.

$$NAS_i(ch) = baseScore_i(ch) \times modifier_i(ch) \tag{1}$$

The equation of $baseScore_i(ch)$ is given in Equation (2) where $usageWeight_{nb}$ is the usage weight of neighbor nb of node i, $caPriority_i$ is the channel assignment priority of node i and NB_i is the set of node i's neighbors. From the equation, it can be observed that a channel that is unavailable to node i is immediately made undesirable to node i by giving it a low NAS value of 0.0. As a result, a node does not select and tune to a channel that is unavailable.

$$baseScore_i(ch) = channelAvail_i(ch) \times \sum_{nb \in NB_i} (usageWeight_{nb} \times channelAvail_{nb}(ch) \times A) \quad (2)$$

where:

$$channelAvail_i(ch) = \begin{cases} 1.0 & \text{if channel } ch \text{ is available to node } i \\ 0.0 & \text{otherwise} \end{cases}$$

$$A = \begin{cases} 1.0 & \text{if } caPriority_i > caPriority_{nb}, \forall nb \in NB_i \\ B^i_{nb} & \text{otherwise} \end{cases}$$

$$B^i_{nb} = \begin{cases} tunedToChannel_{nb}(ch) & \text{if } caPriority_i < caPriority_{nb} \\ 1.0 & \text{otherwise} \end{cases}$$

$$tunedToChannel_{nb}(ch) = \begin{cases} 1.0 & \text{if neighbor } nb \text{ is tuned to channel } ch \\ 0.0 & \text{otherwise} \end{cases}$$

The equation of $modifier_i(ch)$ is given in Equation (3) where $numActive\ NbsOnChannel_i(ch)$ is the number of node i's active neighbors that are tuned to channel ch and $numActive\ Nbs_i$ is the number of node i's active neighbors. The function is used to differentiate two equally preferable channels (same base score) by letting the channel that is currently tuned to by more node i's active neighbors having higher NAS value. This feature of NAS serves to prevent nodes from alternating between channels of equal quality too frequently.

$$modifier_i(ch) = \begin{cases} 0.7 + 0.3 \times \dfrac{numActive\ NbsOnChannel_i(ch)}{numActive\ Nbs_i} & \text{if } numActive\ Nbs_i > 0 \\ 1.0 & \text{otherwise} \end{cases} \quad (3)$$

2.2.4. *Distributed channel assignment.* In distributed channel assignment schemes, nodes coordinate among themselves for channel assignment without intervention or help from a human network moderator. In this subsection, we describe how this is done based on the proposed NAS channel metric.

In Equation (2), it is observed that the channel assignment priorities of different nodes ($caPr\text{-}iority_i$) are used when a node calculates the NAS values of the channels available in the network. In CR-EAOMDV, nodes that flow more traffic are given higher priority in channel assignment. A node uses the number of packets that passes through it within a certain timeframe (HELLO interval) as its priority in channel assignment and advertises this value to its neighboring nodes periodically using HELLO packets. A local leader node initiates a new channel reassignment process at periodic intervals as follows. First, it re-evaluates all the channels in the network according to NAS. After that, it reconfigures its non-default network interfaces to the channels with the highest NAS values. Finally, it broadcasts a new control packet called CHANNELUPDATE. When a CHANNELUPDATE is received by another node, it is processed following the steps shown in Figure 3.

3. Performance Evaluation.

3.1. **Simulation setting.** We present the performance evaluation work done in this section. The evaluation was performed in NS-2. We compared the proposed CR-EAOMDV with several comparable protocols: i) DGA [6], ii) AOMDV-MR, iii) CAODV [3], iv) CA-AODV [7], and v) AOMDV [8]. In our simulations, the nodes are placed in a region of 800-by-800m^2. The IEEE 802.11g ERP-DSSS physical layer is simulated and the type of traffic used is CBR over UDP transport protocol. In all tests, each simulation scenario

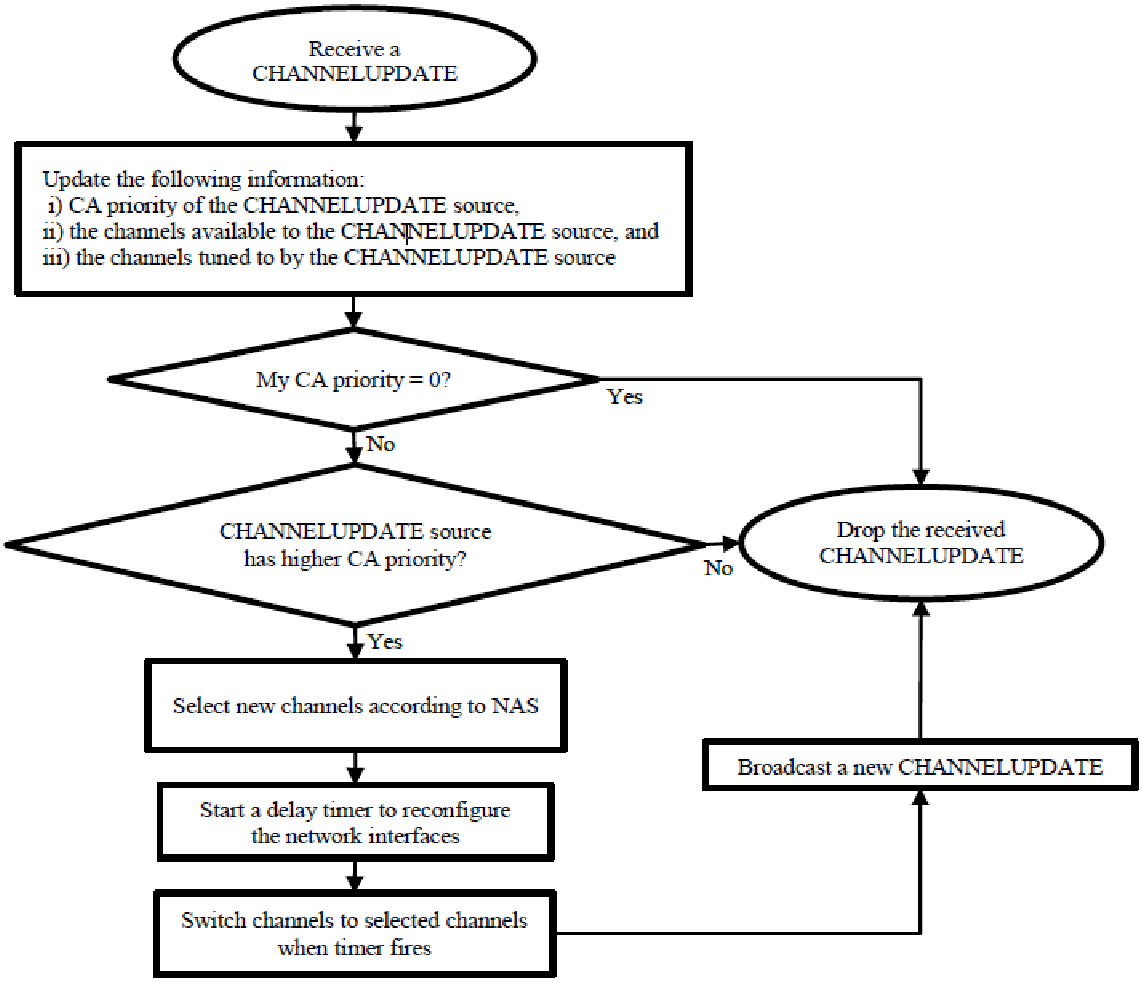

FIGURE 3. Flow chart for processing a received CHANNELUPDATE

is repeated 20 times using different seed numbers and the set of seed numbers used across all protocols is made equal to ensure a fair comparison. The average of the results are used when comparing among different protocols.

3.2. **Results and analysis.**

3.2.1. *Performance in multi-channel WSNs.* We compare the protocols in multi-channel WSNs. The independent variable in this test is traffic flow rate and it is varied from 240Kibps to 1200Kibps in increments of 240Kibps ($1\text{Ki} = 2^{10} = 1024$, $1\text{K} = 10^3 = 1000$). The control variables and their corresponding values used in this test are: i) number of network interfaces per node, n_i : 3, ii) number of nodes: 35, iii) maximum node transmission range, R: 250m, and iv) number of traffic flows: 10.

Figure 4 shows the total network throughput obtained when the number of channels in the network, $n_c = 3 = n_i$. As $n_c = n_i$, in CR-EAOMDV, AOMDV-MR, ERI-CAODV, ARI-CAODV, CA-AODV, and E2-CA-AODV, nodes are tuned to the same channels. From the figure, we observed that CR-EAOMDV, AOMDV-MR and ERI-CAODV performed quite equally. Due to the low amount of channels available, DGA performed only moderately. AOMDV performed worst and this is expected because it is a single channel routing protocol where nodes are able to use only one network interface and channel.

Figure 5 shows the total network throughput obtained as the value of n_c is 3 for CR-EAODMV, AOMDV-MR and DGA respectively. The graphs for the other protocols are not given because their performance is invariant to the change in the value of n_c. From Figure 5, we observed that the throughput obtained by CR-EAOMDV is quite consistent

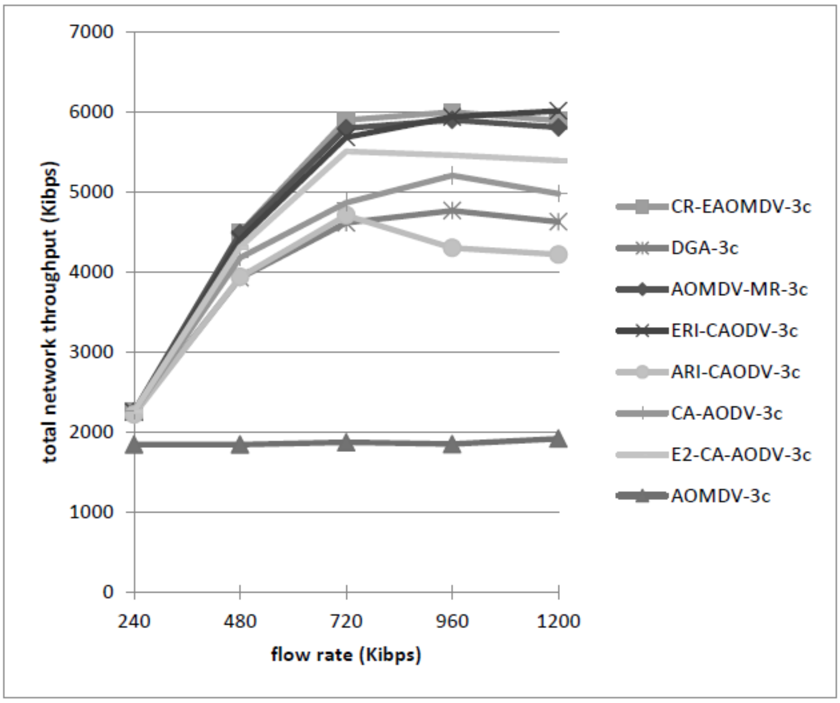

FIGURE 4. Total network throughput vs. traffic flow rate

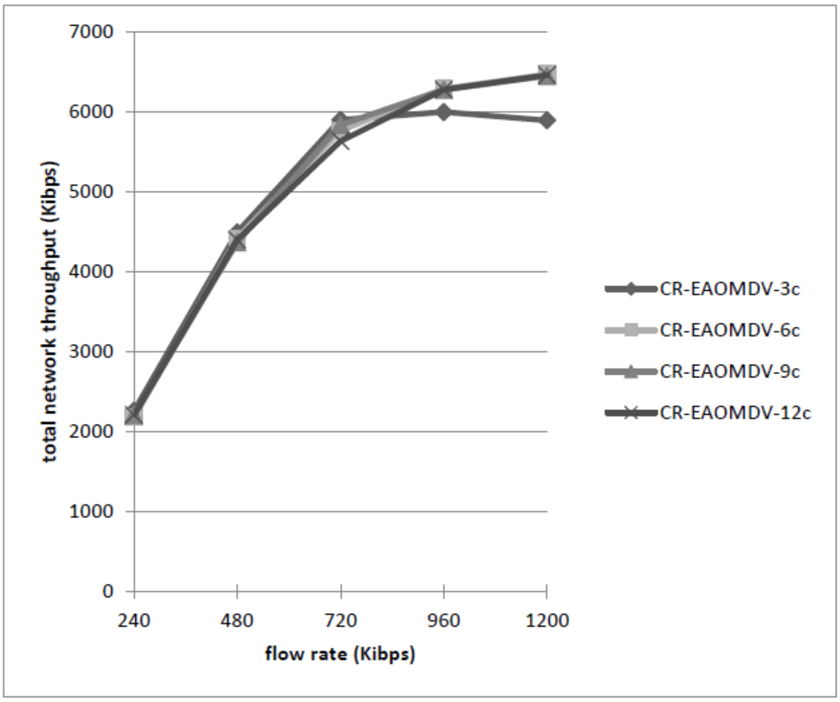

FIGURE 5. total network throughput vs. traffic flow rate for various values of n_c in CR-EAOMDV

with the change in the value of n_c as the throughput lines for the various values of n_c are quite converged.

3.2.2. *Performance in CR-WSNs.*

1) Varying number of PUs

We begin by investigating the effect of number of licensed users on secondary/CR network performance. We conducted this test under two different scenarios: i) number of channels in the network, $n_c = 3$, and ii) $n_c = 6$. In both scenarios, the control variables

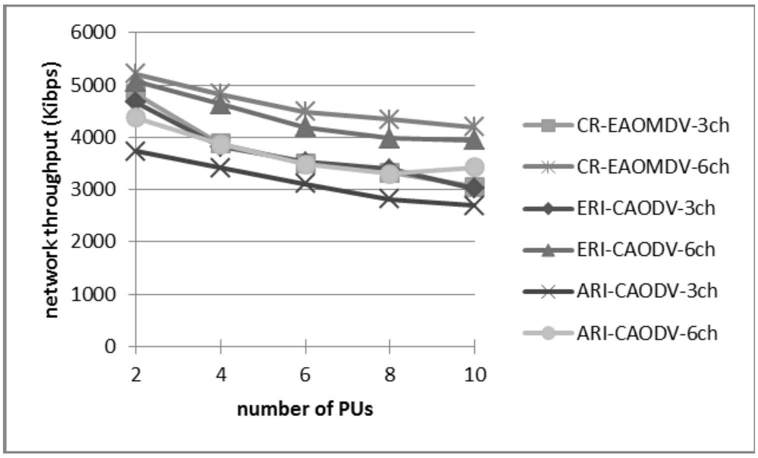

Figure 6. Network throughput vs. number of licensed users

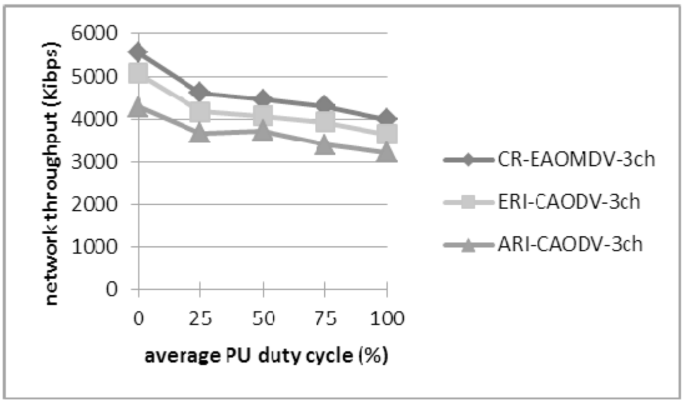

Figure 7. Network throughput vs. average licensed users duty cycle

and their corresponding values are: i) number of network interfaces per unlicensed user, n_i : 3, ii) average T_{off} duration: 10s, iii) average T_{on} duration: 10s, iv) licensed user interference range: 250m, v) number of unlicensed users: 35, vi) maximum unlicensed user transmission range, R: 250m, vii) number of traffic flows: 10, and viii) traffic flow rate: 640Kibps. Figure 6 shows the total network throughput obtained. From the figure, we observed that throughput decreases with increase in the number of licensed users regardless of the protocol used. This is expected because there are less spectrum holes that unlicensed user s can exploit when there are more licensed user s. We also observed that all protocols performed better when there are more channels in the network.

2) Varying PU duty cycle

In this section, we investigate the effect of average licensed user duty cycle on secondary/CR network performance. The control variables and their corresponding values are: i) number of channels in the network, n_c: 3, ii) number of network interfaces per unlicensed user, n_i: 3, iii) number of licensed user s: 5, iv) average duration of a licensed user activity period (combined ON and OFF state): 20s, v) number of licensed users: 35, v) maximum unlicensed user transmission range, R: 250m, vi) number of traffic flows: 10, and vii) traffic flow rate: 640Kibps. Figure 7 shows the total network throughput obtained. From the figure, we observed that for all protocols, the throughput decreases as the average duty cycle of licensed user increases. This is expected because a licensed user occupies its channel for longer periods of time when the duty cycle is set higher. As a result, there are less spectrum holes that the unlicensed user s can exploit. When there are no spectrum holes, unlicensed users have no choice but to revert to the common control channel for their transmissions.

4. **Conclusion.** In this paper, a novel distributed joint channel assignment scheme is proposed. We modelled the proposed scheme in ns-2 and compared it with other comparable channel assignment schemes in multi-channel WSNs. From the simulation results, we observed that the proposed scheme outperforms other protocols. In CR-WSNs, we observed that while the proposed scheme is only able to perform on-par with one of its competitors when the number of channels in the network is equal to the number of network interfaces nodes are equipped with, it usually manages to outperform the competitor when the number of channels in the network is higher than the number of network interfaces nodes are equipped with. This shows that in the proposed scheme, nodes are able to actively exploit the spectrum holes to improve network performance.

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