CAEER: CHANNEL ASSIGNMENT AND ENERGY-EFFICIENT ROUTING PROTOCOL IN COGNITIVE RADIO ADHOC NETWORK

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ABSTRACT - *One of the main challenging factors for designing routing protocols in cognitive radio ad-hoc network (CRAHNs) is how to select route for which can save energy battery for devices and avoid interference to primary users (PU). To solve this problem. In this paper, we propose channel assignment and energy-efficient routing (CAEER) protocol in multi-hop and multi-channel CRAHNs. The proposed routing scheme suggests an intelligent multi-channel selection function, which is used to assign an appropriate channel for link to build route based on interference avoidance to PUs. Moreover, our routing metrics also consider necessarily the path which reduces energy consumption and control overhead. Our simulation results show that CAEER performs better than weighted cumulative expected transmission time (WCETT) and Multi-radio Multichannel Ad-Hoc on-Demand Distance Vector (MM-AODV) protocols in term of energy consumption and the control overhead.*

Keywords *- Cognitive radio, Ad-hoc, Channel assignment, Interference avoidance, Energy-efficient, Routing.*

I. INTRODUCTION

In recent years, the fixed radio spectrum for wireless networks is becoming ineffective and wasting precious spectrum resources. According to the Federal Communications Commission (FCC) report that most of fixed spectrum bands (licensed bands) are of low utilization [9], [11] while unlicensed spectrum bands are more and more crowded. For instance, the licensed spectrum includes the UHF/VHF TV frequency bands. The unlicensed spectrum, which user can access freely, includes the industry, scientific and medical (ISM such as IEEE 802.11, IEEE 802.15.4, wireless local area network (WLANs), Bluetooth and ZigBee) and unlicensed national information infrastructure (U-NII) [8].

To solve this problem, cognitive radio (CR) [1], [16] has been considered as a promising technology for using the valuable spectrum frequency band opportunistically without harmful interference to the PUs. CR devices can identify sense, transfer and access the unused portion of the available spectrum band called spectrum opportunity. Cognitive radio ad hoc networks (CRAHNs) consists of a collection of PDA, Pocket PC, laptop, etc., that work on different spectrum bands (channels) and usually use battery energy. There are two types of users in CRAHNs: one is primary user (PU), which works on its licensed spectrum band (e.g., TV broadcast bands and some cellular bands). The other is cognitive user or secondary user (SU), which is equipped multi-interface with capabilities of sensing the available channel (or spectrum hole), to select the best band for communication. Furthermore, in CRHNs, the CR nodes can be self-organized, self-reconfiguration radio frequency and access the licensed band opportunistically when no PU uses that band and vacate the band as soon as PU start working on it. On-demand routing in multi-hop multi-channel CRAHNs faces several new challenges. An essential challenge is the collaboration between the channel assignment (channel decision) and route selection because of random occurring of PU in SU working area and avoiding interference to PUs. Nodes may dynamically work on different available channels. Therefore, routing algorithm should assign available channel for links in order to avoid interference to the PUs on the same channel.

Another challenge is the energy management. Energy-efficient routing algorithm can be achieved high performance and long network lifetime. It also reduces the network partition caused by the energy exhaustion of the intermediate SUs.

The third challenge is the route maintenance and recovery the broken link. Link failure in multi-hop multi-channel CRAHNs can happen due to the mobility of nodes, the sudden appearance of PUs or dead node.

Consequently, how to improve the efficiency of using available spectrum bands and reduce energy consumption for wireless devices is still an open direction for researchers.

In [11], Probabilistic Path Selection in Opportunistic CR Networks (PPSO) was proposed a novel routing metric, which determines probability lognormal cumulative distribution function (CDF) of the PU-to-CR interference on given channel. Let C^i_{kj}, D and $P^i_{I,j}$ be the maximum channel capacity given by Shannon, the rate demand and the total PR-to-CR interference at CR node j over channel i, respectively. The routing metric is calculated as following:

$$\Pr\left[C^i_{kj} \geq D\right] = \Pr\left[P^i_{I,j} \leq \frac{P^i_{rj}}{2^{D/w_i}-1} - N_0\right] \tag{1}$$

Where N_0, P^i_{rj}, W_i denotes the power of the white Gaussian noise, the power of the received signal and bandwidth on channel i, respectively. The route selected will have the highest probability lognormal CDF to become the most probabilistically stable route to the destination node.

The WCETT [6] uses routing metric that was carefully developed to discover high throughput routing path in multi-radio, multi-hop wireless networks, which is calculated as follows:

$$WCETT = (1-\alpha)\sum_{l\in p} ETT(l) + \alpha \times \max_{1\le k\le N} X_k \tag{2}$$

Where α is a tunable constant ($0 \le \alpha \le 1$). N, l and X_k are the total number of channels, the link of path p and the intra-flow interference capture on channel k, respectively. ETT is defined as the "*bandwidth-adjusted*" indicated the bandwidth of channel per the packet transmission delay. In [2], the authors proposed an efficient spectrum-aware dynamic channel assignment (SA-DCA) assigns channels for links on path based on minimum interference to PU nodes [2]. Every CR node has to check the appearance of PU on all channels and calculate the quality of channels to choose the best channel. However, none of the above works consider avoiding interference to PU when the activity of PU is detected and energy saving for PDA devices during transmitting data packet.

In this paper, we propose a routing protocol the channel assignment and energy-efficient routing, namely CAEER, for multi-hop, multi-interface and multi-channel CRAHNs. Our proposed protocol performs the channel assignment based on interference avoidance to PUs. The interference constraint is considered total interference of SUs and PUs on the same channel because if many nodes transmit simultaneously, the sum of interference of their may become seriously. In addition, CAEER selects energy-efficient path to balance the energy consumption among the nodes in the network and increase high throughput performance and decrease normalized routing overhead. The remainder of this paper is organized as follows. Section II presents the framework and Section III describes the details of the channel assignment and energy-efficient routing (CAEER). In Section IV, we evaluate and analysis the simulation results. Finally, we conclude the paper in Section V.

II. THE FRAMEWORK

In this section, we discuss interference and energy consuming model that are important for designing of our energy-efficient and interference avoidance routing metric.

A. System model

In our system model, we assume a heterogeneous multi-interface multi-channel CRAHN, which consists of N SUs and K PUs. The available spectrums are divided into M channels that are orthogonal licensed or unlicensed spectrum bands. The available channels list at each node may not be the same. Node $x \subset (N \cup K)$ has transmission range, interference range and carrier sense range that depend on the different transmitting power. Let M_x and W_x denote the list of available frequency band and bandwidth at node x, respectively, $L_{xy} = M_x \cap M_y$ denote the set of common available bands (channels) of node x and y. Two node x and y can only communicate to each other if and only if $L_{xy} \neq \emptyset$. Let R_T be transmission range of node x, in which nodes are able to receive correctly or overhear the data transmission. R_I and R_{CS} are interference range and carrier sensing range, respectively. The analysis of interference routing metric can be expressed by different parameters as follow:

- Let a={$a^m{}_{xy}$, $a_{xy}{}^m \in (0,1)$}indicate the channel assignment result. If channel m is assigned for link L_{xy}, we defined $a_{xy}{}^m$ =1. If not $a^m{}_{xy}$ = 0.

- I (ll_{xy}, u) represents the minimized interference level of link ll_{xy} on path u, which causes by transmitting simultaneously of SUs in network.

B. Interference Avoidance Analysis

Aravind Iyer et al. introduced additive interference model [14] for wireless channel interference and carry out the capture threshold model, but it does not focus on the heterogeneity components of spectrum interference band. Therefore, in our interference model, we introduce the signal-to-interference-plus-noise ratio (SINR) model which captures the interference experienced by links in wireless network. This model considers the total aggregate interference on channel that cause by simultaneously transmitting PUs and SUs. A wireless communication on the existent links and the interference on channel have closely relationship to each other that is determined by simultaneously transmitting nodes and the environment (e.g. noise level, characteristics fading channel, data rate etc.). More particularly, let $P^m{}_x$ be the transmitting power of PU x on channel m, denoting the transmitting from PU x to PU y, which is combined interference from other transmitters along with ambient noise exceeding PU y's antenna gain that transmission is successful if and only if equation (3) is satisfied:

$$SINR^m_{xy} = \frac{\dfrac{P^m_x}{d^\eta_{xy}}}{N_0 + \sum_{\forall k\in K, k\neq x} \dfrac{P^m_k}{d^\eta_{ky}} + \sum_{\forall h\in N} a^m_{hy} \dfrac{P^m_h}{d^\eta_{hy}}} \ge \beta \tag{3}$$

where N_0 is the ambient noise power level on each channel, d_{xy} denotes the Euclidean distance between nodes x and y, $P^m{}_x$ is the transmitting power of node x on channel m ($P^m{}_x$ will be zero if node x does not transmit data to node y on channel m) and η denotes the path-loss exponent, which depends on the environment and characteristics of channels (η=2 or η=4) [4].

$\sum_{\forall k\in KK, k\neq x}\frac{P_k^m}{d_{ky}^{\eta}}$ and $\sum_{\forall h\in NN}\frac{P_h^m}{d_{hy}^{\eta}}$ represent the total interference of the PUs (not involving PU x) and SUs that simultaneously use the channel m, respectively, The actual value β is the threshold; which indicates a transmission successfully if the SINR is more than threshold value.

If there is no PU, the throughput of CRAHN will be highest and we can achieve the capacity of channel m by the Shannon capacity as.

$$C_{xy}^m = W_m \log_2\left(1+\frac{\frac{P_x^m}{d_{xy}^{\eta}}}{N_0+\sum_{\forall h\in N, h\neq x}\frac{P_h^m}{d_{hy}^{\eta}}}\right) \tag{4}$$

Without loss of generality, we assume that all nodes have the same transmission power, omnidirectional antenna, and noise power level, i.e., $P_x^m = P_k^m = P_h^m$, $\beta = \beta_x = \beta_y$, $\forall x \neq y$ and the transmission range is smaller than the interference range and the carrier sensing range. In order to determine relationship between the transmission range and the interference range in this model, we suppose that PU x only transmits to another PU y on channel m and PU y lies on the bound of circle, which is created by R_T of PU x (it means that their distance d_{xy} is equal R_T). Similarly, a SU h can lie inside the interference range of PU y on channel m, if its distance to the PU y greater y's R_T as shown in Fig. 1. From (3) and assumption above, if have NN SUs transmit simultaneously on channel m, which will be correct due to interference at PU y, as long as.

$$\frac{\frac{P_{xy}^m}{d_{xy}^{\eta}}}{N_0+\sum_{\forall h\in NN} a_{hy}^m\frac{P_{hy}^m}{d_{hy}^{\eta}}} \geq \beta \tag{5}$$

We have,
$$\frac{P_{xy}^m}{d_{xy}^{\eta}} \geq \left(N_0+\sum_{\forall h\in NN} a_{hy}^m\frac{P_{hy}^m}{d_{hy}^{\eta}}\right)\beta \tag{6}$$

The equation (6) is maximized when distance between SU h and PU y is minimized, it is equivalent that.

$$\frac{P_{xy}^m}{d_{xy}^{\eta}} \geq \left(N_0+\sum_{\forall h\in NN} a_{hy}^m\frac{P_{hy}^m}{\left(d_{hy}^{\eta}\right)_{\min}}\right)\beta \tag{7}$$

In this case, we suppose that channel m is assigned to SU h:

$$\frac{P_{xy}^m}{d_{xy}^{\eta}} \geq NN\frac{P_{hy}^m}{(d_{hy}^{\eta})_{\min}}\beta \tag{8}$$

Therefore,
$$d_{hy} \geq \sqrt[\eta]{NN\beta}.d_{xy} \tag{9}$$

We assume a capture threshold of 10dB, NN is one and if the position of PU y is on the border of the circle, which is covered by PU x's transmission, the interference range will be equal $R_I = 1.77827R_T$ [14].

Therefore, in order for node y to sense the channel m, which is busy if

$$\sum_{\forall x\in K}\frac{P_x^m}{d_{xy}^{\eta}}+\sum_{\forall n\in N}\frac{P_n^m}{d_{ny}^{\eta}}+N_0 \geq \beta_{CS} \tag{10}$$

As shown in Fig. 1, we assume the interference range for communication and carrier sensing range [14] $R_T < R_I < R_{CS}$. The interference of SU g does overlap on interference areas with the PU y on the channel m. Therefore, before assigning channel m of link l_{xy} to SU h, we guarantee that whether the condition in (3) and (9) should be satisfied by all links of PUs. If not, in order to protect the PU, we regard that channel m will be not available to SU h and eliminate channel m out of the available channel list of SU h.

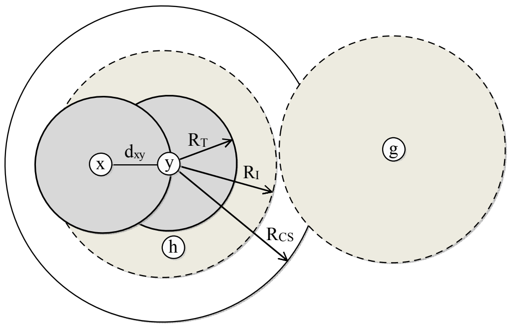

Fig. 1. Interference range

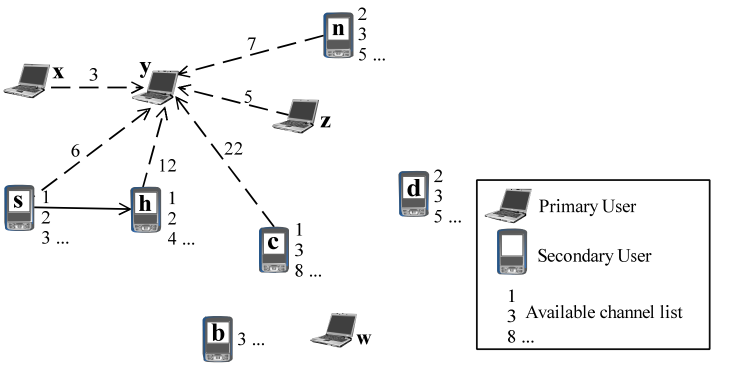

Fig. 2. Calculation in PU y to assign channel 1 for SU h

Fig. 2 illustrates the interference calculation in PU y on link L_{xy} to assign channel 1 of link l_{sh} to SU h. The links in Fig. 2 are L_{xy}, L_{yx}, L_{yz} and L_{zy}. Note that PU w do not have link to y on channel 1, so we do not calculate for $SINR^{1}_{yw}$.

Base on equation (3) and (9), we can calculate SINR level for a transmission from SU s to SU h on channel 1 as we have $SINR^{1}_{xy}$ = 5.204717, $SINR^{1}_{zy}$ =2.89, $SINR^{1}_{yz}$=3.84, $SINR^{1}_{yx}$=2.128 i.e. If all that value are greater than threshold β, we can assign channel 1 for SU s but it is not sure that this value is optimal for all network due to not minimization.

C. Energy consumption model

We consider the energy consumption model of CR user [10] for sending, receiving data packet and idle mode that will reduces according to the parameters as: (i) the NIC model specification, (ii) the size of data packet and (iii) the characteristics of channel. The energy consumption calculation in equation (11), (12) and (13) (in Joules) in idle mode, receiving and sending data packet are varies from 9mA, 230mA and up to 330mA [10] [3], respectively.

$$E_{idle} = (9*5*b)/2*10^{6} \tag{11}$$

$$E_{tx} = (330*5*b)/2*10^{6} \tag{12}$$

$$E_{rx} = (230*5*b)/2*10^{6} \tag{13}$$

where b, E_{tx} and E_{rx} denote number of bits of data packet, the energy consumption for transmitting and receiving b bits, respectively.

Let $E_r(k)$ be the energy residual of a node k at the time t, E_{oh} is energy consumption for overhear a packet, NP is the number of packets, which is sent until time t, we have:

$$E_r(k) = E_{initial} - E_{comsuming}(t) \tag{14}$$

$$E_{comsuming}(t) = NP * (E_{tx} + (NN * E_{rx} - U*E_{oh})) \tag{15}$$

Where NN is average number of one hop neighbor nodes, U is the number of packet, which is overheard at this node.

$$E_{oh}(p) = (230*5 * SizeOfHeader(p)) + (9*5*SizeOfData(p))/2*10^{6} \tag{16}$$

Let E(p) denote the energy consumed in transmitting (and receiving) one packet p on a path from S to D. Then the energy consumed for packet p is:

$$E(p) = \sum_{i=S}^{D} (E_{tx}(p) + E_{rx}(p) + (N_N - 1)E_{oh}(p)) \tag{17}$$

It is clearly that E(p) will minimize the average energy consumed per packet and it will depend on selecting route by shortest-hop count.

Therefore, the average energy residual of the path h can be expressed as following:

$$E(f,u) = \frac{HC_u}{\sum_{k=S}^{D} E_{r(k)}} \tag{18}$$

Where E(f,u) is the energy efficiency of path u on flow f from node S to D. $E_r(k)$ is the residual energy of an intermediate node k in the path u, HC_u is the number of hop of path u (hop count of path u).

We see that the smaller hop count is the less energy consumption and the more energy residual is the better for network. In addition, the smaller hop count gives the packet transmission with comparatively the lower delay network.

D. Routing Constraints and Routing Metric

1. Interference constrain

Let IC={$ic^m_{x,y}$ } denote the interference constrain among SU x and SU y on channel m which is determined by the network topology and transmission range. If $L_{xy} \neq Ø$ and channel m is assigned to link xy then $ic^m_{x,y}$=1, otherwise $ic^m_{x,y} = 0$. Thereby, we have self-interference constraints as below:

Node x cannot receive data packet from more than one node on the channel m, and node x cannot receive and transmit data packet simultaneously on the channel m.

$$\sum_{x\in IT(y)} ic^m_{x,y} + \sum_{k\in IT(y)} ic^m_{y,k} \leq 1 \qquad \forall j\in N, m\in M; \tag{19}$$

Here IT(y) is the set of nodes which is within the transmission range of node y. When node y is receiving data packet from another node on channel m, other nodes, whose location are within the interference range of receiver y cannot transmit data packet on the channel m, i.e.

$$ic^m_{x,y} + \sum_{\substack{h\in IT(k) \\ \forall k\in IR(j), I(i), k\neq i, k\neq j \text{ and } \forall ic^m_{i,j}, m\in M;}} ic^m_{k,h} \leq 1 \tag{20}$$

Where IR (j) is the set of nodes, the location of which is inside the interference range of this received node y. In addition, let OL_{xy} be the set of links of PUs on channel m in the network (all links between PUs in the network) and r(f, u) denote path u for flow f (we assume each flow have many paths). For this reason, before assignment channel m to link between two SUs i and j (set a^m_{ij}=1), if and only if the follow constraint is satisfied:

$$\min_{\forall L_{xy}\in OL_{xy}} SINR^m_{xy} \geq \beta \tag{21}$$

And, we set:

$$ll_{ij} = \min_{\forall m\subset M_i\cap M_j} SINR^m_{ij} \tag{22}$$

Therefore, the objective function can be expressed as:

$$ff = \min \sum_{l_{xy}\in r(f,u)} I(ll_{xy}, u).p(f,u) \tag{23}$$

where ll_{xy} is the minimized interference level received when assign channel m to L_{xy}, p(f, u) denotes the binary indicator for route r(f, u). If we choose route r(f, u) to transmit data, p(f, u)=1; otherwise p(f, u)=0. If we do not use path r(f, u), summary of I (ll_{xy}, u) equals zero and to protect PUs, we will not assign channel m, if the constraint above is not satisfied. If link ll_{xy} is not assigned channel m on route r(f, u), we cannot use this route. Therefore, we have:

$$\sum_{\forall l_{xy}\in u} I(ll_{xy}, u) \leq p(f,u).N_{\max}; \forall r(f,u) \tag{24}$$

$$IC^m_{xy} \geq p(f,u); \forall ll_{xy} \in r(f,u) \tag{25}$$

where N_{max} is a constant used to set up the constraint for the route (i.e., to ensure I(ll_{xy}, u) becomes zero if p(f, u) is zero) and it can be set as the maximum possible for achieve a route.

2. Link interference constraint

The interference over a link must not exceed the maximum interference of channel assigned on that link.

$$\sum_{(l_{xy},u)\in\psi(x,y)} \mathrm{I}(\mathrm{l}_{xy}, \mathrm{u}) \leq \sum_{m\in M_i\cap M_j} I_{\max}(l_{ij}, u).ic^m_{ij} \tag{26}$$

where ψ(x, y) is the set of routes which transmits through link l_{xy}, $I_{max}(l_{ij}$, u) is the max interference of channel m on link l_{ij}.

3. Combined routing metrics

We can combine the desirable properties of the two metrics described above to express the cost function of an end-to-end route can be calculated as follows:

$$Cost = \min\left\{ \sum_{l_{xy} \in r(f,u)} I(ll_{xy}, u).p(f,u)E(f,u) \right\} \tag{27}$$

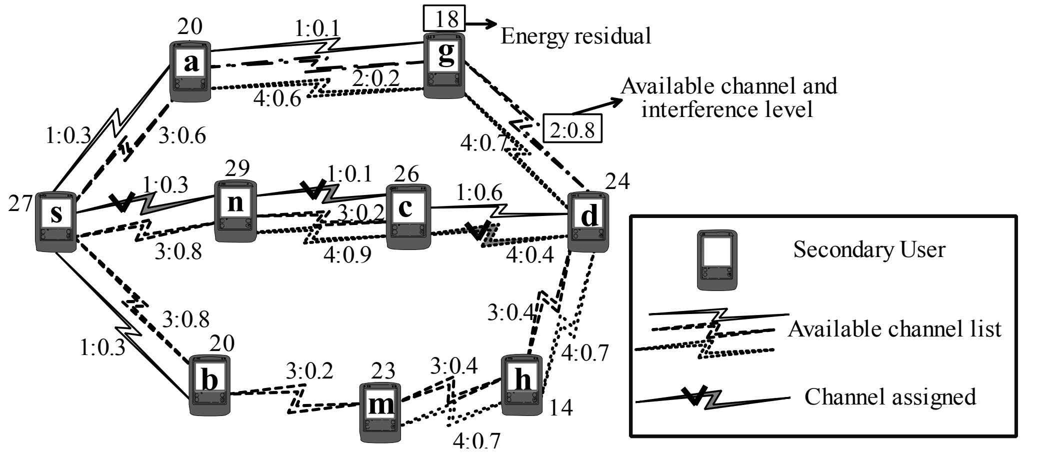

Fig. 3. Example topology with 9 CR and three paths

Fig. 3 shows a simple example with 9 CR nodes to demonstrate the impact of the channel assignment and energy aware routing constraint on the system network. Let us start to compute CAEER routing metric according to equation (21), (22) for three paths from SU s to SU d as follows:

Path 1: SI = [($s^1 \to a^1 \to g^4 \to d^4$) = 1.1, ($s^1 \to a^2 \to g^4 \to d^4$) = 1.2, ($s^1 \to a^4 \to g^4 \to d^4$) = 1.6, ($s^1 \to a^1 \to g^2 \to d^2$) = 1.2, ($s^1 \to a^2 \to g^2 \to d^2$) = 1.3, ($s^1 \to a^4 \to g^2 \to d^2$) = 1.7];

Path 2: SI = [($s^1 \to n^1 \to c^1 \to d^1$) = 1.0, ($s^1 \to n^1 \to c^4 \to d^4$) = 0.8, ($s^1 \to n^4 \to c^1 \to d^1$) = 1.8, ($s^1 \to n^4 \to c^4 \to d^4$) = 1.6, ($s^3 \to n^1 \to c^1 \to d^1$) = 1.5, ($s^3 \to n^4 \to c^1 \to d^1$) = 2.3, ($s^3 \to n^4 \to c^1 \to d^1$) = 2.1, ($s^3 \to n^4 \to c^4 \to d^4$) = 2.1];

Path 3: SI = [($s^3 \to b^3 \to m^3 \to h^3 \to d^3$) = 1.8, ($s^3 \to b^3 \to m^3 \to h^4 \to d^4$) = 2.1, ($s^3 \to b^3 \to m^4 \to h^3 \to d^3$) = 2.1, ($s^3 \to b^3 \to m^4 \to h^4 \to d^4$) = 2.4];

where SI is total aggregation of the interference level of links caused by PUs and SUs. Therefore, interference minimization of Path 1, Path 2 and Path 3 are 1.1, 0.8 and 1.8, respectively.

Assuming that p(f, u) = 1 and applying equation (27), we will have:

Cost = min {1.1*3/89 = 0.0371, 0.8*3/106 = 0.0226, 1.8*4/108 = 0.0667} = 0.0226

Hence, we will select Path 2 for flow from SU s to d and assign available channels for hops as below:

Path 2 = [($s^1 \to n^1 \to c^4 \to d^4$) = 0.8, E_r = 106, HC = 3, Cost = 0.0226] and assignment channel s^1, n^1, c^4, d^4 as shown in Fig. 3.

III. PROPOSED ROUTING PROTOCOL

In this subsection, we describe the CAEER protocol in detail over AODV. The principal feature of CAEER is to access opportunistically available channel, which is unoccupied by PU and switch dynamically among different channels on routes, but it still keeps the energy efficient during data transmission. The detail of the CAEER protocol is consist of three phases; (i) the route discovery, (ii) the route selection phase and (iii) the route maintenance phase that is described as below:

1. Route discovery phase

We suppose that SU s know the list of available channel of network through broadcasting HELLO packet. Whenever the source SU s has data packets to transmit to the destination SU d, it first checks whether route to destination d or not in its routing table. If has, the data packets can be sent immediately to the destination CR by using that route. Otherwise, it will begin a route discover phase process as depicted in Algorithm 1.

Algorithm 1: Route Discovery Phase

for each link $L_{sy,\ s,y\in N}$ **do**
for each channel m on available channels of SU s **do**
  calculate $SINR_{sy}$ level on channel m of SU s as in (3)
  if SINR level on channel m is greater than β for all PUs **then**
    broadcast route RREQ packet to all neighbors on channel m
  else
    remove the channel m in available channel list of SU s
  end if
end for
end for
for each SU $y\in N$ **do**
  SU y receives RREQ from SU s on available channel m;
  if it is the first RREQ of SU s on channel m **then**
    select available channel $m \in L_{sy}$ minimized $SINR_{sy}$ as equation (22);
    update channel m for link L_{sy}, SU y's remaining energy and $SINR_{xy}$ level into RREQ packet
  else
    discard duplicated RREQ packet;
  end if
  if SU y is not destination node **then**
    create a reverse route on channel m to source node from RREQ packet;
    if it is a new route or better reverse route in routing table **then**
      update a reverse route on channel m into routing table
    end if
    broadcast route RREQ packet to all neighbors on each available channels
  else *//if SU y is destination node,*
    wait for threshold time to receive all path from SU s;
    update a reverse route on channel m into routing table;
    call route selection algorithm;
  end if
end for

2. Route selection and assignment phase

During this phase, in the destination SU can receive multiple RREQ control packets, which is sent along different paths and contain full path from source. If the destination SU receives the first RREQ control packets, it will establish a threshold time to collect all RREQ packets when the threshold time is not out of date. At the same time, it also updates the route from RREQ packets into routing table. If the threshold time is expire, it will execute route selection and assignment channel, as described in Algorithm 2.

Algorithm 2: Route Selection and Assignment Phase

if SU d is destination node **then**
  for each a path p in routing table **do**
    calculate route metric as cost function as equation (27);
    select path p with minimum cost value;
    create and send RREP across route p ;
  end for
else *// if SU d is immediate node or source node then*
  receive RREP packet on channel m;
  if SU y is mediate node on route p **then**

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        if route in RREP packet contain a new or better old path then
            update route p in routing table
        else
            assign that channel for link on route p;
            forward RREP packet through that channel;
        end if
    else if SU y is source node on route p then
            update route p in routing table;
            assign that channel for link on route p;
            send all data packets in the queue to this destination node
        else
                discards the RREQ packet;
        end if
    end if
end if
```

3. Route maintenance phase

The broken link may appear when the activity of PU is detected or the mobility of SUs out of network. At that time, nodes with all routes containing the broken link will try to repair locally finding another route in its routing table or the available channel between two CR users. If it cannot recover that link, it will call route discovery phase as line 6 commands in Algorithm 3 below:

Algorithm 3: Route Maintenance Phase

```
// channel m is broken due to occupying by ongoing PU or being mobility
1: if channel m ∈ link L_xy on path p is broken then
2:     find another available channel u ∈ link L_xy with the minimum SINR_xy ;
3:     if found then
4:         update channel u for link L_xy on route p
       else
6:         call route discovery and route selection algorithm ;
7:     end if
8: end if
```

IV. EVALUATION AND SIMULATION RESULTS

In this section, we implement CAEER in the network simulator ns-2 (v.2.34) [17] [18] to evaluate the performance of our proposed protocol considering the impact of different number of available channels and sudden activity of PUs in the simulation time. In addition, we compare the energy efficiency with network lifetime of the CAEER, MM-AODV and WCETT in the same experimental environment and simulation parameters that are described in Table 1.

Table 1. Simulation Parameters

Item No.	Parameter	Value
1	Simulation Area	1000m x 1000m
2	Number of PUs	10
3	Number of SUs	50
4	The transmission range of PUs	250m
5	The transmission range of SUs	160m
6	Number of available channel of each SU	1 - 12
7	Radio Propagation Model	Propagation/Two Ray Ground
8	Channel Type	Channel/wireless channel
9	Antennae mode	Antenna/Omni-antenna
10	Mobility Model	Random Way Point

11	MAC Type	IEEE 802.11
12	Initial Node Energy	30J
13	Energy model	Battery
14	Packet size	512 bytes
15	Simulation time	500s
16	Traffic type	CBR traffic

In Fig. 4, we can see that the number of PUs is higher; the average throughput of SUs is lower. This is because when the number of PUs increases, the available channels will become scarcer and more difficult to find out SUs to build path or SUs have to vacate the channel using, which is occupied by PUs; in other words, if the number of available channels of SUs increase, the average throughput also increase.

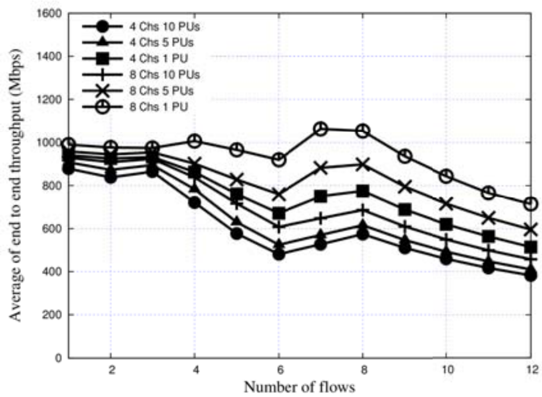

Fig. 4. Aggregate throughput of CAEER as the number of PUs increase.

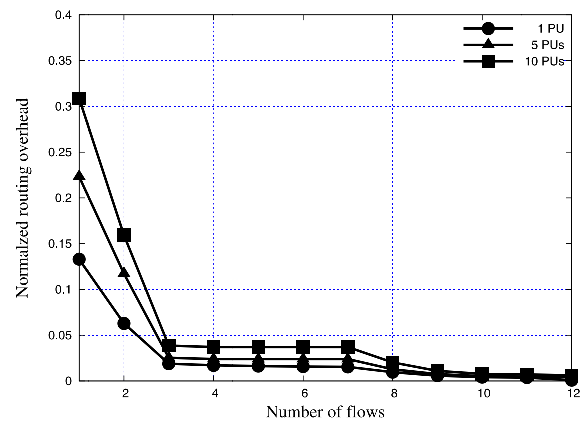

Fig. 5. Normalized routing overhead per number of flows

Fig. 5 shows the normalized routing overhead, which is defined as the number of control packets transmitted per data packet received at the destinations and can be computed as follows:

$$ControlOverHead = \frac{N_{control}}{N_{data}} N_{flow} M \tag{28}$$

where $N_{control}$, N_{data} and N_{flow} are the number of control packets transmitted, the number of data packets received and the number of flows, respectively. We can see clearly that when the number of PUs increase, the routing overhead also increases due to the increase of RREQ, RREP, RREC and RERR. As shown in Fig.6, the normalized routing overhead increase when the number of available channels increases because in the route discovery and route maintenance phase SUs have to send control packets on all channels to choose available channel appropriately for transmitting data packets, but CAEER is still better that MM-AODV and WCETT routing protocols.

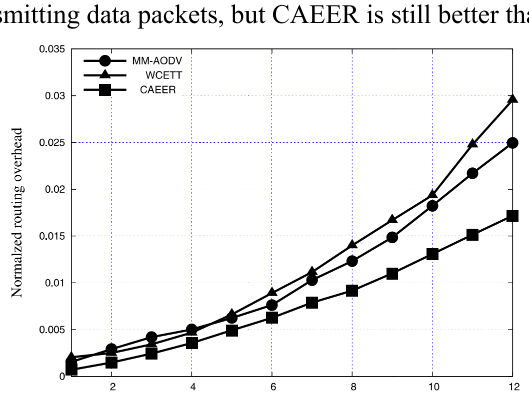

Fig. 6. The normalized routing overhead per number of channels between CAEER and other protocols

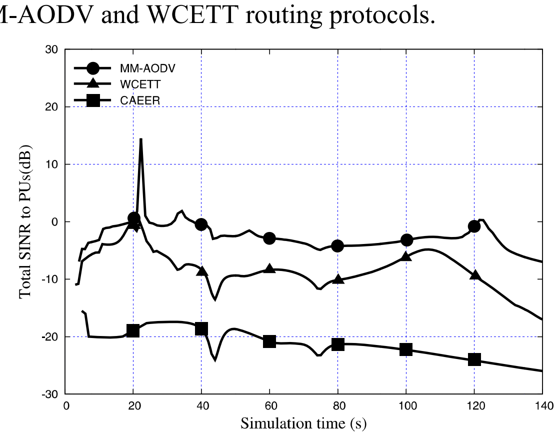

Fig. 7. Total of SINR level to PUs (dB)

In Fig. 7, we fixed the number of channels, PUs and flows to measure the total SINR level to PUs during simulation time. It is clearly that, SINR level of CAEER has the ability to decrease about 15% and 20% compared to the original WCETT and MM-AODV [6], respectively.

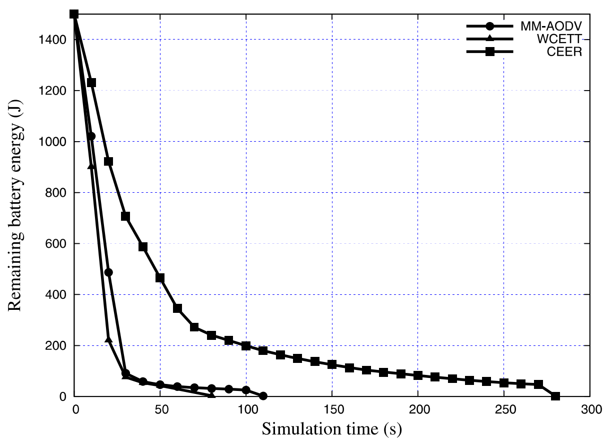

Fig. 8. Remaining battery energy

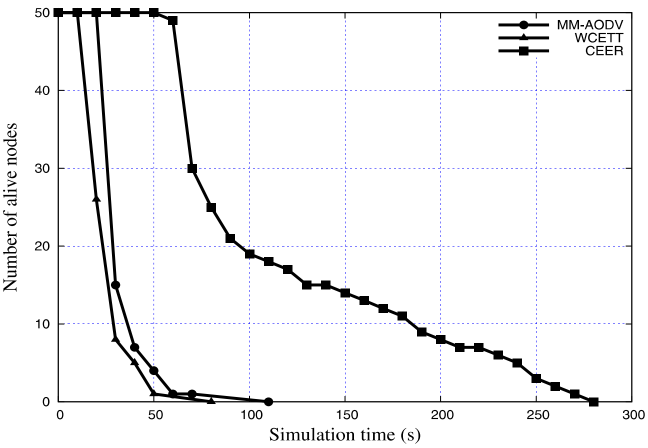

Fig. 9. Number of SUs alive

Finally, the relationship between network energy consumption and network lifetime is shown in Fig. 8 and Fig. 9. In Fig. 8, the remaining battery energy of entire SUs with our proposed routing protocol is greater about 50% than WCETT and MM-AODV. As illustrated in Fig. 9, where show the number of SUs alive per simulation time(s). It is clearly observable that CAEER have longer network lifetime with the first dead node about 250% and 200% in comparison with WCETT and MM-AODV, respectively.

V. CONCLUTIONS

In this paper, we have proposed channel assignment and energy-efficient in multi-hop, multi-interface and multi-channel routing protocol called CAEER in CRAHNs. CAEER combines channel decision and route selection base on interference avoidance to PUs and energy efficiency to establish communications across areas of changing available spectrum hole. Our simulation results show that the performance of CAEER in terms of versus the active of PUs is analyzed through large topology network (50 SUs and 10 PUs) with mobility random way point model. Moreover, our proposed algorithm performs better than MM-AODV and WCETT about consuming energy, decreasing routing overhead, while it guarantee the higher throughput and longer network lifetime.

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CAEER: GIAO THỨC ĐỊNH TUYẾN GÁN KÊNH VÀ HIỆU QUẢ NĂNG LƯỢNG TRONG MẠNG VÔ TUYẾN TÙY BIẾN THÔNG MINH

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TÓM TẮT *- Một trong những nhân tố thách thức chính cho việc thiết kế các giao thức định tuyến trong mạng vô tuyến tùy biến thông minh là chọn tuyến ra sao để cho nó có thể tiết kiệm năng lượng pin cho các thiết bị và tránh nhiễu tới người dùng chính. Để giải quyết vấn đề này. Trong bài báo này, chúng tôi đề xuất giao thức định tuyến gán kênh và tiết kiệm năng lượng (CAEER) trong mạng vô tuyến tùy biến thông minh đa chặng, đa kênh. Lược đồ định tuyến được đề xuất đưa ra một hàm lựa chọn đa kênh thông minh, chúng được sử dụng để gán một kênh thích hợp cho liên kết để xây dựng tuyến dựa vào sự tránh nhiễu tới người dùng chính. Hơn nữa, các độ đo định tuyến cũng xem xét tuyến cần thiết, nó giảm năng lượng tiêu thụ và tổng chi phí điều khiển. Các kết quả mô phỏng của chúng tôi cho thấy rằng giao thức CAEER thực hiện tốt hơn giao thức WCETT và MM-AODV về tiêu thụ năng lượng và tổng chi phí điều khiển.*