Joint Channel Assignment, Stable Routing and Adaptive Power Control in Mobile Cognitive Networks

Jin Zhou†, Feilong Tang†,‡, Jie Li$^{\varsigma,\S}$, Wenchao Xu$^{\pounds}$, Minyi Guo§
†School of Software, Shanghai Jiao Tong University, Shanghai, China
‡State Key Lab. for Novel Software Technology, Nanjing University, P.R. China
$^{\varsigma}$Faculty of Engineering, Information and Systems, University of Tsukuba, Japan
§Department of Computer Science & Engineering, Shanghai Jiao Tong University, Shanghai, China
$^{\pounds}$Department of Communication Engineering, East China Normal University, Shanghai, China
zhou413369343@sjtu.edu.cn; {tang-fl, guo-my}@cs.sjtu.edu.cn; jieyi.lee@gmail.com; wchxu@ce.ecnu.edu.cn

***Abstract*—Most existing routing algorithms assume wireless nodes use maximal transmission power or set up the power at the beginning of the network configuration. These static approaches potentially introduce signal interference that can be mitigated through power control. In this paper, we propose a *Joint Channel assignment, stable Routing and adaptive Power control (JCRP)* approach that dynamically controls the transmission power to avoid the channel interference for improving the channel utility. Our JCRP allows a node to control its transmission power to a certain value at which it has a longest channel conflict-free time. Besides, we propose a novel routing metric *integrated selecting stability (ISS)* to measure the quality of links, which considers node mobility and channel interference, together with the dynamical power control. The simulation results demonstrate that our JCRP significantly outperforms the related routing algorithms in terms of network throughput.**

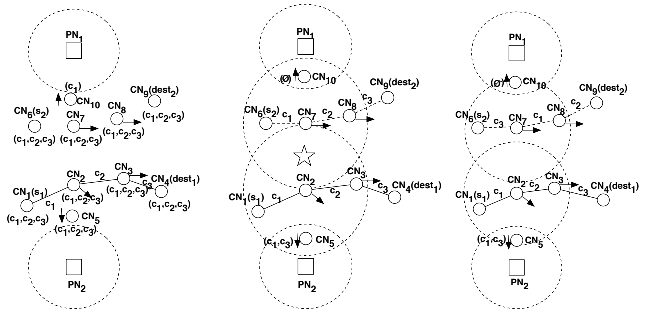
I. INTRODUCTION

Cognitive radio can partially solve the spectrum scarcity problem through the dynamical spectrum access [1], in which cognitive nodes (CNs) can opportunistically adapt unused spectrum licensed to primary nodes (PNs) and dynamically vacate the channel when the corresponding PN activates the channel again [2],

In mobile ad hoc cognitive networks (MACNets), stable routing plays an important role because the network performance highly depends on the stability of routes selected by routing protocols [3], [4]. However, the stability of routes significantly suffers from the node mobility and the co-channel interference among both CNs and PNs. Moreover, available channels of a route frequently change with PN activities and the node mobility [5]. Note that the degree of the signal interference directly depends on the node transmission power. The more the power is, the more the interference range will be. As a result, the route selection, channel assignment and power control should be jointly considered [2], [6] during route setup and data transmission.

In existing related work, the power of nodes is configured at very beginning of the life of networks, and each node transmits at the fixed power level until it eventually runs out of energy, which debases the utility of limited wireless spectrum. To improve the spectrum efficiency, in this paper, we propose a *Joint Channel assignment, stable Routing and adaptive Power control* (JCRP) approach through adaptive and dynamical power control, as shown in Fig.1.

In Fig.1(a), each CN has a set of available channels marked below the nodes. PN_1 and PN_2 are using their licensed channel c_1 and c_2, respectively. CN_6 will set up a route to CN_9. To select a links with longer duration, the route from CN_6 to CN_9 is set up as shown in Fig.1(b). For the simplicity, we assume that the interference radius is equal to transmission radius represented by dotted circles in this scenario. As a result, there is a channel interference in any way to assign the channels to $Path_2$, marked with a star in Fig.1(b), between CN_7 and CN_2. In order to avoid interference between CN_7 and CN_2, JCRP will reduce transmission power to a certain value and assign stable channels, so that there is no channel confliction between them, as shown in Fig.1(c).



(a) Initial topology (b) No power control (c) Power control

Fig. 1. Motivating scenario for our JCRP.

Our JCRP focuses on making a path available as long as possible by combining node mobility, channel assignment and power control. To fully reduce conflict among channels, we integrate the power control with the construction and recovery of the route. Compared with existing schemes, our approach

978-1-4799-8406-0/15/$31.00 ©2015 IEEE

significantly improves system performance in mobile cognitive environments through considering the stability of the links and cross-layer design. Main contributions of this paper are summarized as follows.

- We propose a new routing metric *integrated selecting stability* (IIS) to predict the link quality, which considers *movement offset degree (MOD)* to capture the link stability suffering from the node mobility and *channel offset degree (COD)* to predict the channel stability suffering from the signal interference.
- We adapt the power control to avoid channel interference and to improve channel utility in two phases: the route setup and the route recovery. In both phases, nodes adaptively control their transmission power to avoid the channel confliction or enable the route to continue to transmit data.
- We propose and implement a novel cross-layer approach JCRP, which combines network layer, MAC and node power, to minimize the channel interference and improve the network throughput in MACNets.

II. NETWORK MODEL AND PROBLEM STATEMENT

We firstly present a network model, and then formulate the JCRP problem. Finally, we propose the channel interference model in MACNets.

A. Network Model

We model a MACNets as an undirected graph $G = (V, E)$, where V is the union of CN set (V_c) and PN set (V_p). E is the union of CN links (E_c) and PN links (E_p). Each CN is equipped with a common control channel (CCC) to transmit control messages, such as routing packets. Let N_i represent a node and l_{N_i,N_j} represent the link on which node N_j is within node $N_i's$ communication radius. There are K data channels in the network. We use C_{N_i} to represent the available channels of node N_i. Let C_{N_i,N_j} represent the available channels for a link l_{N_i,N_j}. Let UCS_{N_i} represent the channels assigned to the node N_i now. We assume that each node N_i has different transmission radius $R_T^{N_i}$ and interference radius $R_I^{N_i}$, and $R_I^{N_i} = \beta R_T^{N_i} (\beta > 1)$; and the relationship between power p_{N_i} and transmission radius $R_T^{N_i}$ is the same as that in [7]. There are m data flows in the network. Each node knows its own location(such as through GPS) and can periodically send their information to its neighbor nodes, including the location information, routing information and control information.

B. JCRP Problem

To formulate the JCRP problem, we firstly define some notations. $ISS_{f_i}^{l_{u,v}^c}$ is a new routing metric we develop to predict the stability of $l_{u,v}$ on a channel c for f_i, which will be described in the following. $P_u^{min}(t)$ means the minimal transmission power of node u at which it can still keep connecting to the nodes at time t. $P_{u:c}^{\max}(t)$ represents the maximal transmission power of node u at which it does not interfere to any other node on channel c at time t. $p_u^c(t)$ represents the power of node u to be set up at time t on channel c. t_{f_i} represents the traffic generated by data flow f_i in a unit of time.

$$max \qquad T = \sum_{i=1}^{m} t_{f_i} \tag{1}$$

Formula (1) is the optimization objective, i.e., maximizing network throughput, of the JCRP problem. Next, we will describe the constraints of the JCRP problem. Constraint (1) is that when JCRP is setting up a route, every node will select the next hop according to the metric ISS, which will make sure that each link has a maximal ISS. Constraint (2) is that we should promise that channels are not interfered by each other when the route is setting up. Constraint (3) is that the power control of each node will make sure the data is transmitted normally not only on itself, but also on the other nodes, i.e., $P_u^{min}(t) \leq p_u^c(t) \leq min\{P_{max}, P_{u:c}^{max}(t)\}$; $\forall u, v \in V_u; \forall c \in C_{u,v}$. Constraint (4) is that we should provide a requirement that each link will be bi-connection. Constraint (5) is that all the data will not be loss. Constraint (6) is that JCRP should provide a guarantee that any node can use mostly K channels simultaneously. Constraint (7) is that the transmission rate of any node is not greater than the maximal bandwidth, represented by w_v.

The JCRP problem is a mixed nonlinear integer programming. In general, it is NP-hard. In this paper, we solve this problem by proposing a heuristic algorithm which joints selecting stable route based on movement stability, channel stability and controlling transmission power in an interference-avoiding way.

C. Channel Interference Model

Signal interference among links occurs only when they are using the same channel. We propose an interference graph to capture interferences for a link $l_{u,v}$ on f_i as shown in Fig.2.

Let $\bigcup\limits_{\text{i}} node_{u:c}^i$ and $\bigcup\limits_{\text{i}} r\_node_{u:c}^i$ represent the set of nodes that are in the interference area of the node u and the set of nodes in whose interference areas the node u is, respectively. Both of them are assigned with the same channel c. The colors of the squares are only used to distinguish the interfering node sets. We assume that before $l_{u,v}$ is set up, there are no channel conflictions. Therefore, the nodes in squares are conflict-free. The goal is to remove the solid line between the circles and the squares when a link $l_{u,v}$ is being set up.

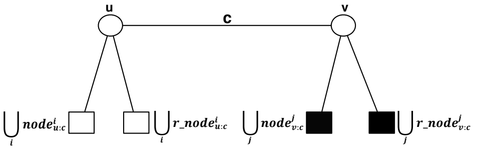


Fig. 2. Interference graph.

III. JOINT CHANNEL ASSIGNMENT, STABLE ROUTING AND ADAPTIVE POWER CONTROL (JCRP)

This section firstly presents channel stability prediction, then proposes a new routing metric to quantitatively evaluate the stability of links, and finally proposes channel assignment, power control and JCRP algorithms.

A. Channel Stability Prediction

In MACNets, the stability of a link $l_{u,v}$ is affected by the quality of the channel that it uses. We develop a new matric called *Channel Offset Degree (COD)* to predict the channel stability. Let $COD_{l^{c_i}_{u,v}}$ represent the minimal time when $l_{u,v}$ can use channel c_i, which is formulated as follows.

$$COD_{l^{c_i}_{u,v}} = min\{\bigcup_{j}\bigcup_{k} TIME\left(l^{c_i}_{u,v}, l^{c_i}_{j,k}\right) | j,k \in V, \quad j \neq u, k \neq v\} \tag{2}$$

$TIME(l^{c_i}_{u,v}, l^{c_i}_{j,k})$ represents the time from $l_{u,v}$ using channel c_i to $l_{u,v}$ disconnecting due to the channel conflict with $l_{j,k}$. Note that a node z enters the interference area of a node o, when it meets the formula $d_{z,o}(t) \leq R^o_I$. $d_{z,o}(t)$ represents the distance between node z and node o at time t. By solving the inverse function of the formula, the time that the node z will be interfered by the node o is formulated as T^o_z ($T^o_z \geq d^{'}_{z,o}(R^o_I)$). Since both u and v will cause $l_{u,v}$ to disconnect, we get the formula as follows,

$$TIME(l^{c_i}_{u,v}, l^{c_i}_{j,k}) = min\{\bigcup_{z \in \{u,v\}} \bigcup_{o \in \{j,k\}} T^o_z\} \tag{3}$$

The stability of the channel will be affected by the mobility of the nodes. To address this problem, we use a probability-based approach proposed by Literatures [8], [9] to predict the movements of nodes.

$$COD^{C_{u,v}}_{l_{u,v}} = (max\{\bigcup_{i=1}^{m} COD_{l^{c_i}_{u,v}}\}) \times P(max\{\bigcup_{i=1}^{m} COD_{l^{c_i}_{u,v}}\}) \tag{4}$$

B. Routing Metric

In MACNets, the stability of a link $l_{u,v}$ mainly suffers from node mobility and channel interference. We proposal a novel routing metric, called *integrated selecting stability* (ISS) , to capture the above factors.

$$ISS^{f_i}_{l_{u,v}} = MOD_{l_{u,v}} + \delta COD^{C_{u,v}}_{l_{u,v}} \tag{5}$$

$ISS^{f_i}_{l_{u,v}}$ represents the stability of a link $l_{u,v}$ on f_i. $COD^{C_{u,v}}_{l_{u,v}}$ reacts the stability of the channels. $MOD_{l_{u,v}}$ represents the time from the link $l_{u,v}$ being set up to its connection failure. Here connection failure means a link cannot transmit data because the distance between the two nodes is longer than the transmission radius. δ is a factor which shows how important the channel conflict is to the selection of the next hop when the route is being set up. Through experiments, we find that δ depends on the amount of the flows, the number of the channels and the mobility of the nodes.

We assume that the mobility of each node follows *Random Waypoint* (RWP) model. In this case, the duration time (DT) of a link $l_{u,v}$ is the value of t when $d_{u,v}(t) = R^u_T$, recorded as $T_{u,v}$. We use T_{v,PN_i} , which is the value of t when $d_{v,PN_i}(t) = R^{PN_i}_I$, to represent the DT between v and PN_i. In JCRP, when we select the next hop node v, the data transmission time $t^c_{u,v}$ of $l_{u,v}$ will be considered. That is $t^c_{u,v} = \frac{S^c_{u,v}}{r^c_{u,v}}$, where $S^c_{u,v}$ represents the data size of the node u transmitted on the channel c to the node v; $r^c_{u,v}$ represents the data transfer rate of $l_{u,v}$ on the channel c. If $t^c_{u,v} < T_{v,PN_i}$, it means that the data transmission on the link $l_{u,v}$ has been completed before v enters the interference area of PN_i. Therefore, the node v is the candidate node in our algorithm. Note that we will also add the node v to the candidate nodes, if $T_{u,v} < T_{v,PN_i}$, it means the link $l_{u,v}$ will be connection failure before the node v enters the interference area of PN_i.

Combined with the duration time of $l_{u,v}$ and the probability of changes in mobility of u and v, we come to the MOD of $l_{u,v}$.

$$\mathrm{MOD}_{l_{u,v}} = DT_{l_{u,v}} \times P\left(DT_{l_{u,v}}\right) \tag{6}$$

where $DT_{l_{u,v}} = \min\left\{\mathrm{t^c_{u,v}}, \mathrm{T_{u,v}}, T_{v,PN_i}\right\}$.

C. Channel Assignment

In the channel assignment, our principle is to avoid the channel conflicting with the PNs, and to ensure minimally interfere with the CNs. We define the set of the primary nodes that interfere with the node u as *Interference Set* (IS_u), which is represented as follows.

$$IS_u = \{PN_i | d_{u,PN_i}(t) \leq R^{PN_i}_I \;\; \&\& \;\; R^{PN_i}_I \;\; is \;\; active\} \tag{7}$$

We define the set of available channels of u as follows.

$$C_u = CS \backslash \{C_j | C_j \; is \;\; used \;\; by \;\; PN_i \;\; \&\& \;\; PN_i \in IS_u\} \tag{8}$$

CS represents all the channels in the networks. When $C_u = \emptyset$, it means that the node u has no available channels to transmit data. At this time, JCRP will set $COD^{C_{u,v}}_{l_{u,v}} = -\infty$, and this will also make $ISS^{f_i}_{l_{u,v}}$ infinitely small. Therefore, JCRP will ignore the node v, when the node u is selecting the next hop in route selection.

To avoid the channel conflicting with the PNs, we use factor η to constrain the use of the channels that are used by the primary nodes. Note that when $\eta < 0$, JCRP will also set $COD^{C_{u,v}}_{l_{u,v}} = -\infty$ to exclude this channel.

$$\eta = \frac{min\left\{d_{u,PN_j}, d_{v,PN_j}\right\}}{R^{PN_j}_I} - 1 \tag{9}$$

Let $\bigcup_j UCS_{PN_j}$ represent the set of channels that are used by the primary nodes. For a channel c_i ($c_i \in \bigcup_j UCS_{PN_j}$) on $l_{u,v}$, we calculate its COD by multiplying the factor η with $COD^{c_i}_{l_{u,v}}$. The goal is to have priority to avoid the interference with the primary nodes by reducing the probability of the primary channel assigned.

D. Power Control

In this section, we illustrate power control with power control policy and power control algorithm.

1) Power Control Policy: Our routing metric only accounts for the interference from other nodes to the current node, without considering its interference with other nodes, so it needs to control power to avoid the interference of node itself with other nodes.

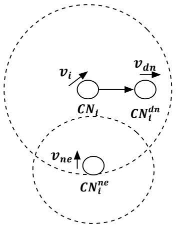


Fig. 3. Signal interference.

In Fig.3, the dotted circles have the same meaning with Fig.1. We assume that the CN_i is any node that is going to adjust transmission power. Let NE_{CN_i} represent the nodes which are assigned with at least one channel that is being used by CN_i. Let DN_{CN_i} represent the nodes which are directly connecting to CN_i. CN_i^{ne} is the nearest node from CN_i in NE_{CN_i}; CN_i^{dn} is the furthest node from CN_i in DN_{CN_i}. All the three nodes have arbitrary velocity, represented by v_i, v_{ne}, v_{dn} respectively. Let $v_{u,v}$ represent the relative velocity of node v to node u.

If $v_{u,v} > 0$, it means v is moving towards u; otherwise, v is moving away from u. We assume that when u is controlling power, $v_{u,v}$ will remain the same.

We make OP_{CN_i} as the optimal power of CN_i to be set, at which, the corresponding transmission radius and interference radius are $OR_T^{CN_i}$ and $OR_I^{CN_i}$ respectively. Let $R_{T:max}^{CN_i}$ and $R_{I:max}^{CN_i}$ represent the maximal transmission radius and interference radius of CN_i respectively. Our power control algorithm follows that it cannot affect the existing route. So CN_i when controlling power needs to make two guarantees at the same time: guarantee the normal transmission of its data flow (data flow going through CN_i) and that of other node data flows (data flow not going through CN_i). Note that in the power control, we put the second guarantee as the priority.

Policy 1: if $v_{i,dn} >= 0$, then $OR_T^{CN_i} = d_{CN_i,CN_i^{dn}}$.

In this case, We just set $OR_T^{CN_i}$ to $d_{CN_i,CN_i^{dn}}$, which will meet the first guarantee and satisfy the second guarantee to a greatest extent.

Policy 2: When $v_{i,dn} < 0$, $v_{i,ne} <= 0$, if $d_{CN_i,CN_i^{ne}} \leq R_{I:max}^{CN_i}$, then $OR_I^{CN_i} = d_{CN_i,CN_i^{ne}}$; else, $OR_I^{CN_i} = R_{I:max}^{CN_i}$.

If $v_{i,dn} < 0$, $v_{i,ne} < 0$, it means CN_i^{dn} and CN_i^{ne} are both moving away from CN_i, so OP_{CN_i} should be adjusted to the maximum, which can fully satisfy the first guarantee. In order to satisfy the second guarantee, we have to make $OR_I^{CN_i} = d_{CN_i,CN_i^{ne}}$. If $v_{i,dn} < 0$, $v_{i,ne} = 0$, it means CN_i^{dn} is moving away from CN_i, but the relative distance between CN_i and CN_i^{ne} keeps the same. We should still make $OR_I^{CN_i} = d_{CN_i,CN_i^{ne}}$, which just makes CN_i^{ne} cannot enter the interference area of CN_i and satisfy the first guarantee to a greatest extent at the meantime. Note that $d_{CN_i,CN_i^{ne}}$ may be bigger than $R_{I:max}^{CN_i}$. In this case,it means the optimal power of CN_i is bigger than the maximal power of CN_i, so we should only set $OR_I^{CN_i}$ to $R_{I:max}^{CN_i}$.

Policy 3: When $v_{i,dn} < 0$, $v_{i,ne} > 0$, if $\frac{|v_{i,ne}| \times d_{CN_i,CN_i^{dn}} + |v_{i,dn}| \times d_{CN_i,CN_i^{ne}}}{|v_{i,ne}| + \beta |v_{i,dn}|} \leq R_{T:max}^{CN_i}$, then $OR_T^{CN_i} = \frac{|v_{i,ne}| \times d_{CN_i,CN_i^{dn}} + |v_{i,dn}| \times d_{CN_i,CN_i^{ne}}}{|v_{i,ne}| + \beta |v_{i,dn}|}$; else, $OR_T^{CN_i} = R_{T:max}^{CN_i}$.

Our purpose is to make the two guarantees be broken at a latest point. Make $T_T^{CN_i^{dn}}$ and $T_I^{CN_i^{ne}}$ represent the time CN_i^{dn} moving outside the transmission area of CN_i and CN_i^{ne} moving into the interference area of CN_i, respectively. In order to get the longest guarantee period, we must make $T_T^{CN_i^{dn}} = T_I^{CN_i^{ne}}$.

$$T_T^{CN_i^{dn}} = \frac{OR_T^{CN_i} - d_{CN_i,CN_i^{dn}}}{|v_{i,dn}|} \tag{10}$$

$$T_I^{CN_i^{ne}} = \frac{d_{CN_i,CN_i^{ne}} - OR_I^{CN_i}}{|v_{i,ne}|} \tag{11}$$

Considering the linear relationship between the $OR_T^{CN_i}$ and $OR_I^{CN_i}$, we finally get the formula,

$$OR_T^{CN_i} = \frac{|v_{i,ne}| \times d_{CN_i,CN_i^{dn}} + |v_{i,dn}| \times d_{CN_i,CN_i^{ne}}}{|v_{i,ne}| + \beta |v_{i,dn}|} \tag{12}$$

Note that if $\frac{|v_{i,ne}| \times d_{CN_i,CN_i^{dn}} + |v_{i,dn}| \times d_{CN_i,CN_i^{ne}}}{|v_{i,ne}| + \beta |v_{i,dn}|} > R_{T:max}^{CN_i}$, it also means the optimal power of CN_i is larger than the maximal power of CN_i. In this case, we set $OR_T^{CN_i}$ to $R_{T:max}^{CN_i}$.

2) Power Control Algorithm: In JCRP, the power control algorithm is needed to execute in the two processes: the process of route setup and the process of route recovery. For route setup, the power control is to improve the stability of the route. For route recovery, it is to reduce the times of route reconstruction. In both processes, they all follow the power control policy as described above.

The pseudo-code of the power control algorithm (PCA) of JCRP is presented in algorithm 1. When a node CN_i wants to control its transmission power, PCA will first set up NE_{CN_i} and DN_{CN_i}. After marking the two nodes CN_i^{ne} and CN_i^{dn}, PCA will calculate $v_{i,ne}$ and $v_{i,dn}$ respectively. Note that when $d_{CN_i,CN_i^{ne}} \leq d_{CN_i,CN_i^{dn}}$, it means the node CN_i cannot control its power, since any power adjustment will lead either its own link or other links to fail.

Algorithm 1: Power Control Algorithm (PCA)

```
for each node $CN_i$ to adjust power
    set up $NE_{CN_i}$
    set up $DN_{CN_i}$
    $d_{CN_i,CN_i^{ne}} = +\infty$
    $d_{CN_i,CN_i^{dn}} = -\infty$
    for each node $NE_i \in NE_{CN_i}$
        if($d_{CN_i,NE_i} < d_{CN_i,CN_i^{ne}}$)
            $\{d_{CN_i,CN_i^{ne}} = d_{CN_i,NE_i};\ CN_i^{ne} = NE_i\}$
    for each node $DN_i \in DN_{CN_i}$
        if($d_{CN_i,DN_i} > d_{CN_i,CN_i^{dn}}$)
            $\{d_{CN_i,CN_i^{dn}} = d_{CN_i,DN_i};\ CN_i^{dn} = DN_i\}$
    if($d_{CN_i,CN_i^{ne}} \leq d_{CN_i,CN_i^{dn}}$)
        return FAILURE;
    compile $v_{i,ne}$, $v_{i,dn}$
    set up $p_{CN_i}$ using power control policy.
```

Algorithm 2: JCRP

```
1:  $ISS\,[u] = -\infty$
2:  set up the set of candidate neighbour nodes $V_n$ with launch angle $\alpha$
3:  while($V_n \neq \emptyset$) do
4:      set $v$ as the first element in $V_n$
5:      $ISS^{f_i}_{l_{u,v}} = MDT_{l_{u,v}} + \delta COD_{l_{u,v}}$
6:      if($ISS\,[u] < ISS^{f_i}_{l_{u,v}}$)
7:          $\{ISS\,[u] = ISS^{f_i}_{l_{u,v}};\ \mu = v;\ c_{u,\mu} = c_{u,v}\}$
8:      $V_n = V_n - v$
9:  end while
10: if($ISS\,[u]\ ==\ -\infty$) $\{\alpha = \alpha + \Delta\alpha$; goto step 3;$\}$
11: $SSP_{s_i} = SSP_{s_i} + \mu$
12: $USC_{s_i,dest_i} = USC_{s_i,dest_i} + c_{u,\mu}$
13: adjust the transmission power of $u$ to $p_u$ by PCA algorithm
14: update route packet with $SSP_{s_i}$ and $USC_{s_i,dest_i}$, and send it to $\mu$ with $p_u$
```

E. Routing Algorithm With Adaptive Power Control

JCRP approach is to establish routing through establishing links step by step. Given that the source node is s_i, and the destination node is $dest_i$. When setting up route, the current working node u according to the maximum value of $ISS^{f_i}_{l_{u,v}}$ to determine the next-hop node v, until $v = dest_i$.

Current work node u only selects the neighbour nodes within its launch angle α (e.g., 90^o) towards the destination to calculate the $ISS^{f_i}_{l_{v,u}}$, and will add $\Delta\alpha$ (e.g., 30^o) if there is no candidate node. Note that when calculating the ISS, the channel will also be assigned at the same time. After it sends this information through the routing packet to the next-hop node v. The major information included in the routing is: *sender, destination, packet ID, flow ID, sub-selected path* SSP_{s_i}*, and assigned channel set* $USC_{s_i,dest_i}$. Among these, SSP_{s_i} represents a collection of the nodes that the current route goes through. $USC_{s_i,dest_i}$ represents the set of the channels assigned to the current route from s_i to $dest_i$. Once a node v receives the routing package, it will become the new working node to select the next hop by JCRP. Algorithms 2 describes the JCRP, where SSP_{s_i} is cumulated hop by hop until $dest_i$ becomes the working node. When $dest_i$ receives the routing package, it will immediately responds the routing information including SSP_{s_i} and $USC_{s_i,dest_i}$ to the source node s_i via the inverse path of SSP_{s_i}. On receiving the information, s_i begins to transmit data through SSP_{s_i} on $USC_{s_i,dest_i}$.

IV. PERFORMANCE EVALUATION

We developed a simulation system, which is built on the NS2 simulator [10] with power adjustment and multi-channel extensions, to evaluate our JCRP approach and compare it with the related protocols AODV [11] and PCTC [8].

A. System Setting

PNs and CNs are randomly deployed and move at a speed randomly distributed in [0, V_{max}]. Channels comply with the Two-Way Rayleigh model. PNs have the fixed transmission radius and interference range. Each PN_i is assigned a fixed channel and randomly uses it.

All CNs share the same common control channel. Each CN has multiple available data channels. In the experiments, we tested different performance metrics for 500s. Each flow is generated through NS2-based FTP data generator and transferred through a TCP connection. Other parameters are listed in Table 1.

TABLE I

Parameters	*Values*
PN transmission range R_T^{PN}	125m
PN Interference range R_I^{PN}	250m
Packet size (S_{packet})	512KB
Number of totally available channels (K)	13
Number of CN (N)	50
Number of PN (M)	5
Maximal speed (V_{max})	10m/s
Number of data flows (m)	5

B. Aggregated System Throughput

We use the *aggregated system throughput* (AST), which is the sum of concurrent data flows, to compare the parallel transmission ability of our JCRP with AODV and PCTC in the following scenarios.

Concurrent data flows. With the increase of concurrent data flows, AST in JCRP and PCTC is also increasing while the rising trend of AODV which generally keeps unchanged is not apparent. According to Fig.4, AST in both JCRP and PCTC is increasing, but the increase rate of JCRP is much higher than that of PCTC. Especially when the sum of the concurrent data flows reaches 4, the increase rate of JCRP is much higher than that of both PCTC and AODV, which could be explained that

JCRP can control the transmission power to avoid channel conflict, when concurrent data flows increases, resulting in more serious interferences among channels. The reason why concurrent data flows has little influence on the throughput of AODV is that AODV is a flooding protocol. Though the data flows increase, the competition of the channels between data flows and the interferences of PNs are stronger, resulting in the increase rate of the overall throughput is not high.

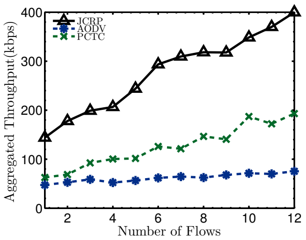


Fig. 4. Number of flows.

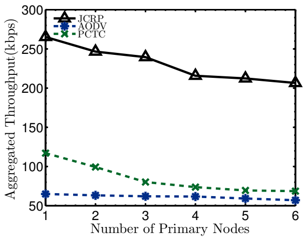


Fig. 5. Number of primary nodes.

Primary nodes. The more PNs, the fewer channels that CNs can utilize, since CNs are unable to impact the transmission among PNs. According to Fig.5, with the increase of the number of PNs, the throughput of JCRP, PCTC and AODV tends to decrease. However, the throughput of JCRP is still apparently larger than the other two, which can be explained that when PNs are using a certain channel, JCRP is able to make the surrounding nodes choose different channels to transmit data. In addition, JCRP decides the next node through predicting the time when the CNs enter the interference area of PNs, which is able to not only avoid interfering PNs, but also increase the effectiveness of the whole path.

Node mobility. The mobility of nodes has great impact on the stability of routes. According to Fig.6, with the increase of mobility of nodes, the throughput of PCTC and AODV decreases while JCRP keeps stable and high throughput though it has tiny fluctuates. The high throughput of JCRP results from the prediction of node mobility by JCRP while the fluctuations are caused by its adaptive power control.

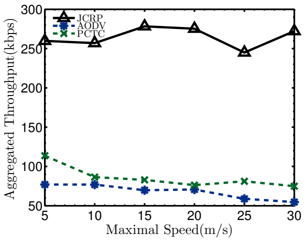


Fig. 6. Maximal speed.

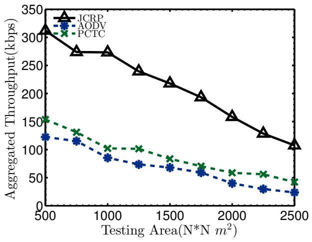


Fig. 7. Network area.

Network area. With the extension of network area, density of CNs correspondingly decreases and the average distance among CNs becomes larger, which causes the links among CNs disconnect, to a great extent, due to the insufficient distance for data transmission, and then the throughout decreases. According to Fig.7 with the extension of network area, the throughput of JCRP, PCTC and AODV decreases, especially that of JCRP, which can be explained by the adaptive power control of JCRP. When the network area extends, to a great extent, CNs need to use the largest power to transmit data, so the advantages of adaptive power control of JCRP is less and less effective.

V. CONCLUSIONS

We presented the JCRP approach that jointly selects stable route, assigns channels and adaptively controls transmission power for MACNets. Firstly, we developed a routing metric ISS that captures the node mobility and the channel interference. We, then, proposed the adaptive power control algorithm to avoid the channel inference. Finally, we proposed the JCRP approach. Compared with related work, our approach optimizes route stability not only by jointing routing selection and channel assignment but also by dynamical power control. Comprehensive experiment results demonstrate that our JCRP significantly improves network throughput in MACNets.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (NSFC) project (Nos. 61373156, 91438121, 61202025 and 61428204), the Key Basic Research Project (No. 12JC1405400) and the Shanghai Pujiang Program (No. 13PJ1404600) of the Shanghai Municipality, the National Basic Research Program (973 Program, No. 2015CB352403), and Shanghai Branch of Southwest Electron and Telecom Technology Research Institute Project (No. 2013008).

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