POWER CONTROL FOR UNDERGROUND COGNITIVE RADIO MANET USING SMART ANTENNAS

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ABSTRACT

A new power control mechanism is proposed for the deployment of a smart-antennas-equipped MANET (Mobile Ad hoc NETwork) in a confined environment, already populated by many fixed radio devices (primary network) sharing the same scarce frequency band. Using small messages constantly broadcasted by primaries, MANET nodes can approximate the distance and direction of the fixed primaries in their surrounding, as well as the MANET aggregate interference these primaries are experiencing. The proposed mechanism offers great potential, for underground mine tunnel deployment of MANET, since advances in millimeter radio waves technologies will soon make smart antennas easily portable in size. Our contribution lies in the possibility for MANET nodes to use the approximated interference they may cause to the primary network before transmission, with their directional transmission beam, so as to constantly control their transmission power to lower their impact on the primary network QoS.

1. INTRODUCTION

A confined indoor environment, such as an underground mine with many narrow tunnels, is a perfect scenario where a smart-antennas-equipped MANET (Mobile Ad hoc NETwork) could offer great benefits. Using a smart antenna, a network node is not restricted to transmit/receive with an omni-directional antenna radiation pattern. Instead, by means of multiple antennas at the transceiver, forming an antenna array, a node can smartly choose the direction and width of its radiation beam by properly tuning its transceiver tap weight coefficients. In a mine tunnel, there is no need to waste radiation power towards walls since the electromagnetic waves cannot pass through thick rock surfaces. Furthermore, reflections and refractions caused by rough wall surfaces are likely to cause multipath, thus reducing the expected data rate [1]. This transmission and reception directivity may also be exploited to allow different networks to coexist in close proximity even if they share the same frequency band, since spectrum is a very scarce resource [2].

Nowadays, a smart antenna transceiver has an adequate size and weight to equip vehicles used in underground mines. However, with advances in millimeter radio waves technologies, such a transceiver could be wore by a single person in the very near future. In the context of a MANET (secondary network) deployed in the same area of a fixed legacy wireless network (primary network), using the same frequency band, the sensing function is one of the most important attributes of cognitive radios - as it ensures non-interference to licensed users - and should involve more sophisticated techniques than simple determination of power in a frequency band [2]. Figure 1 presents a typical scenario of our research context.

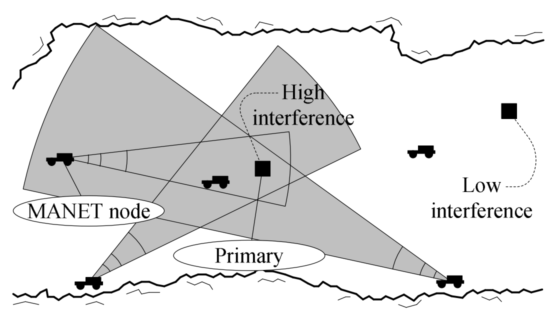

Figure 1: *Underground cognitive radio MANET using smart antennas.*

In [3], pilots allow secondary network users to measure the local SNR of the primary signal which is used to approximate the distance from a primary transmitter. This way, secondary users can adjust their transmission power accordingly to avoid interfering with primaries. However, since this gives too little information about the primaries, secondary users must be quiet within a "no-talk radius". Not only is the secondary network penalized in this scheme by using only omni-directional antennas, but also for never knowing the actual aggregate interference it causes to the primary network.

Our present research interest is focused on taking advantage of a minimum of information the primary network can transmit to the MANET, so that MANET nodes can control their directional transmission power to avoid interfering with primaries. In our scheme, the primaries constantly broadcast small messages in order the let the MANET nodes be aware of the amount of interference each primary can still tolerate, and, upon reception of such a message, nodes can approximate the distance and direction of the signal source. Power control is done independently at each node from this precious information.

The purpose of the present paper is to show an efficient and promising way to control directional transmission power in a cognitive radio context. The power control mechanism described will be used in a future work for a directional neighbor discovery algorithm. Each MANET node will have to discover its 1-hop neighbors while controlling its transmission power, as required by the primary network.

2. MODELS

The well-known Random Waypoint model [4], largely used in the literature, will be used to simulate the mobility of each node composing the MANET. For the primaries, no mobility model will be associated. At the beginning of a simulation, each primary has a uniformly distributed 2D location inside the rectangle area used for the nodes mobility model. Each node of the MANET has only one half-duplex transceiver. The same frequency band is used by both the MANET and primary network. There is no possible communication between both networks, except the constantly broadcasted messages from the primaries to help MANET nodes know primaries aggregate interference and relative position. The measured SNR of a primary message is used by a node to approximate the distance from it, the measured angle of arrival is used to approximate the direction, and the small payload of this message only contains the aggregate interference that a primary is currently experiencing from the MANET.

We omit temporal details about whether communication amongst nodes is synchronous (like TDMA) or asynchronous (like CSMA), and the protocols used, as those are unlikely to influence our future simulations results. We then assume for all our future work that time is divided into time frames of equal length (duration). When a listening node receives a packet from a transmitting node, the packet is either accepted (error free) or rejected. A maximum of one packet can be accepted by a listening node at the end of each frame. The frame length is chosen by considering the used data rate, the mean packet size (including payload, header and trailer), and also a guard time for some real-world constraints.

The constant maximal aggregate interference that each primary can tolerate from the MANET, I_{MAX}, is known by every node. In the following subsections, the set of all primaries is defined as S_P, and the set of all transmitting nodes at a given instant (frame) is defined as S_T.

2.1. PROPAGATION AND ANTENNA MODEL

We use roughly the same antenna model as in [5]. Suppose we have a transmitting node *i* and listening node *j*. Let $G_T(i) = 2\pi/\theta(i)$, where $G_T(i)$ is the antenna gain of the transmitting node *i*, with its beam width $\theta(i)$ and beam direction $\phi(i)$. Similarly, let $G_L(j) = 2\pi/\theta(j)$, where $G_L(j)$ is the antenna gain of the listening node *j* with its beam width $\theta(j)$ and beam direction $\phi(j)$. Antenna beams are modelled as circle sectors.

Let $d(i,k)$ be the distance between *i* and any receiver *k* (listening node or primary). The path loss gain $G_\alpha(i,k)$ with path loss exponent *α* of the transmitted power as a function of $d(i,k)$, by considering a constant unitary gain for a distance smaller than the reference distance d_0, is defined by:

$$G_\alpha(i,k) = \begin{cases} 1, & \forall d(i,k) \in [0, d_0] \\ d(i,k)^{-\alpha}, & \text{otherwise} \end{cases}. \quad (1)$$

Let $\psi(i,k)$ be the angle between positions $(x(i), y(i))$ and $(x(k), y(k))$ of node *i* and receiver *k*, respectively. Also, let $\Delta_T(i,k) = |\phi(i) - \psi(i,k)|$ and $\Delta_R(i,k) = |\phi(k) - \psi(i,k)|$. Since $\psi(i,k)$, $\phi(i)$ and $\phi(k)$ are angles indicating a direction, they must be relative to the same reference. We define a binary gain $G_{TL}(i,j)$, taking either the value 1 or 0, depending on whether the listening node *j* can receive transmitted power from node *i* as per the width and direction of both antenna beams, by the following equation:

$$G_{TL}(i,j) = \begin{cases} 1, & \text{if } \left(\Delta_T(i,j) \le \dfrac{\theta(i)}{2}\right) \wedge \left(\Delta_R(i,j) \le \dfrac{\theta(j)}{2}\right) \\ 0, & \text{otherwise} \end{cases}. \quad (2)$$

We define a protection circle of constant radius R_P around each primary *p*, and thus centered at $(x(p), y(p))$. We consider that node *i* causes interference to primary *p* if its transmission circle sector overlaps *p*'s protection circle, even if it may not reach its center. The idea of considering such a protection circle comes from the present model assumptions. Indeed, that simple model suits our needs for the MANET communication, but the lack of precision in getting the approximate position of primaries, from their broadcasted small messages, underestimates the potential interference a transmitting node may actually cause to one or more primaries. This includes errors in estimating distance and direction of arrival from a received message, and also lack of precision in estimating radio wave propagation, especially in underground mines [1,6]. We then consider the interference caused by node *i* to primary *p* as the interference *p* would experience if *i*'s circle sector reaches *p*'s circle center. Let $\beta(i,p)$ be the angle formed by two lines tangents to the protection circle of a primary *p*, on opposite sides of it, and joining at node *i*, as shown on Figure 2.

We define a binary gain $G_{TP}(i,p)$, taking either the value 1 or 0, depending on whether node *i* can cause interference to primary *p* as per the width and direction of its antenna beam, by the following equation:

$$G_{TP}(i,p) = \begin{cases} 1, & \text{if } \Delta_T(i,p) < (\theta(i)/2 + \beta(i,p)/2) \\ 0, & \text{otherwise} \end{cases}. \quad (3)$$

If we let $P_T(i)$ be the transmission power of node *i*, and $P_R(i,j)$ be the received power at node *j*, then we have:

$$P_R(i,j) = P_T(i) G_T(i) G_L(j) G_\alpha(i,j) G_{TL}(i,j). \quad (4)$$

Similarly, if we let $I_R(i,p)$ be the interference received at primary *p*, with the assumption that all primaries have an omni-directional antenna with unitary gain, then we have:

$$I_R(i,p) = P_T(i) G_T(i) G_\alpha(i,p) G_{TP}(i,p). \quad (5)$$

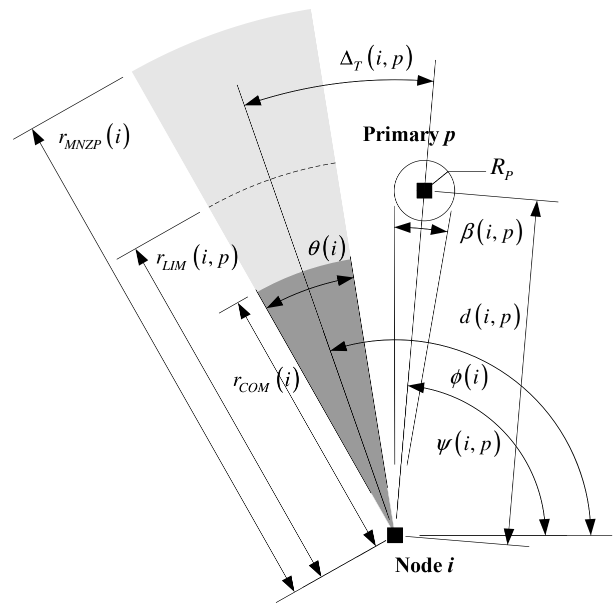

Figure 2: *Visual representation of the variables defining the relation between a transmitting node and a primary.*

Let $I_{Ag}(p)$ be the aggregate interference from the MANET at primary p, then:

$$I_{Ag}(p) = \sum_{\forall h \in S_T} I_R(h,p) . \tag{6}$$

When primary p broadcasts a message for the MANET, its payload contains $I_{Ag}(p)$ only.

Because of power attenuation as a function of distance, from a transmitting node, the received power might be so small at a listening node or primary that it becomes irrelevant, even as interference, so we consider it to be null. Hence, we define the *MNZP* (Minimal Non Zero Power) as the power threshold from which any lower power is automatically set to null. When a transmitting node i uses the transmission power $P_T(i)$, we consider the distance from node i's position, at which the power reaches *MNZP*, to be $r_{MNZP}(i)$. The variables $r_{LIM}(i,p)$ and $r_{COM}(i)$, shown on Figure 2, are defined in the following subsection.

2.2. Interference and Communication Model

We assume the maximal transmission power of the primaries to be much lower (by using UWB communication, for example) than the maximal transmission power of the MANET nodes, for the frequency band composing the unique control channel used by the latter. The chosen constant noise power N_R, at the listening nodes, takes into account the interference generated by the primaries to the MANET, in addition to the thermal noise. However, we consider the transmission power used by each primary p to transmit the message, containing $I_{Ag}(p)$, to be high enough so that it can be properly received by nodes from a respectable distance.

We use roughly the same interference model as in [7]. Let γ_{SINR} be the SINR threshold above which a packet transmitted by node i is considered error free when received by a listening node j, in the presence of other interfering transmitted packets from each other transmitting node h. The condition for a packet to be accepted is then:

$$\frac{P_R(i,j)}{N_R G_R(j) + \sum_{\forall h \in S_T \setminus h \neq i} P_R(h,j)} > \gamma_{SINR} . \tag{7}$$

A listening node j is said to be in communication range of a transmitting node i if, by supposing there is no interference caused by any other transmitting node, it has its SNR above γ_{SINR}. The distance from node i's position of this communication range is considered to be $r_{COM}(i)$.

We assume the possibility for each node to know $I_{Ag}(p) \forall p \in S_P$, prior to start any transmission. Then, before transmitting, a node has to choose a transmission power meeting the following requirement:

$$\nexists p \in S_P \left| I_{Ag}(p) > I_{MAX} \right. . \tag{8}$$

3. Proposed Power Control Mechanism

In order to meet the requirement (8), we assume the possibility for each transmitting node i to also predict $I_{LIM}(i,p) \forall p \in S_P$ prior the start any transmission, where $I_{LIM}(i,p)$ is the interference upper limit for which node i predicts $I_{Ag}(p) \leq I_{MAX}$ upon transmission, if it uses the maximal allowable transmission power $P_{MAX}(i,p)$ it has to calculate.

We define $r_{LIM}(i,p)$ as the distance where the interference power at primary p would reach $I_{LIM}(i,p)$, from node i transmitting at power $P_{MAX}(i,p)$. If $G_{TP}(i,p)=0$, node i predicts that $I_{LIM}(i,p)=0$ and $P_{MAX}(i,p)=\infty$ does not need to be calculated as the transmission will not affect $I_{Ag}(p)$. In that case, the value of $r_{LIM}(i,p)$ is then just not considered as shown by the arbitrary value it has on Figure 2. On the other hand, if $G_{TP}(i,p)=1$, we have the following relation from our propagation model:

$$I_{LIM}(i,p) = P_{MAX}(i,p) G_T(i) * \begin{cases} 1, & \forall r_{LIM}(i,p) \in [0, \mathrm{d}_0] . \\ r_{LIM}(i,p)^{-\alpha}, & \text{otherwise} \end{cases} \tag{9}$$

The following subsection presents our proposed power control mechanism to find the right limit radius $r_{LIM}(i,p)$ in order to get $P_{MAX}(i,p) \forall p \in S_P$.

3.1. Finding the Limit Radius

Two cases may occur when $G_{TP}(i,p)=1$, depending on the value of $\Delta_T(i,p)$, which influences the way we calculate $r_{LIM}(i,p)$.

The first case occurs if $\Delta_T(i,p)\in\left[0,(\theta(i)/2)\right]$, for which we have to find the value of $r_{LIM}(i,p)$ such that the resulting arc on i's circle sector is tangent to p's circle. Then we simply have $r_{LIM}(i,p)=d(i,p)-R_P$.

The second case occurs if

$$\Delta(i,p)\in\left]\frac{\theta(i)}{2},\left(\frac{\theta(i)}{2}+\frac{\beta(i,p)}{2}\right)\right[, \tag{10}$$

for which the grey triangle formed on Figure 3 guides us to find the value of $r_{LIM}(i,p)$.

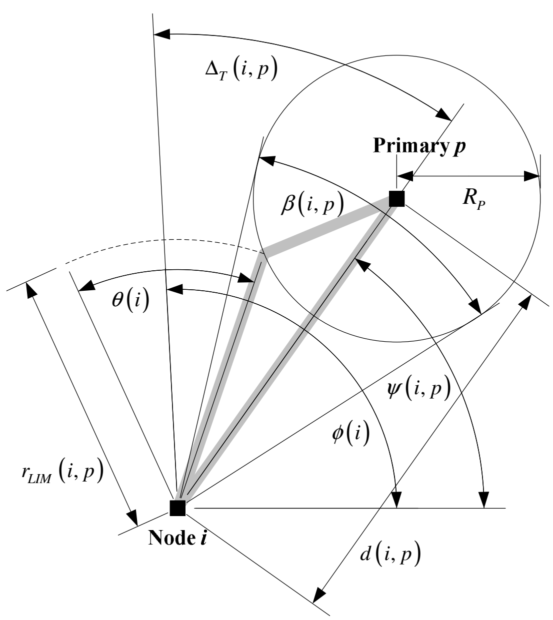

Figure 3: *Visual representation of the second case in calculating the limit radius.*

We assign this grey triangle sides to $a=r_{LIM}(i,p)$, $b=d(i,p)$, $c=R_P$, and also the only already known angle $\omega_C=\Delta_T(i,p)-\theta(i)/2$. Hence, we get the order 2 polynomial as a function of a:

$$a^2-2b\cos(\omega_C)a+(b^2-c^2)=0, \tag{11}$$

with roots given by:

$$a=b\cos(\omega_C)\pm\sqrt{b^2(\cos^2(\omega_C)-1)+c^2}. \tag{12}$$

The smallest root of this polynomial gives the length of a intersecting with p's circle without passing through it yet, while the greatest root gives the length of a passing through the circle before intersecting with it. Thus, we are only interested in the first root, and $r_{LIM}(i,p)$ is given by:

$$r_{LIM}(i,p)=d(i,p)\cos\left(\Delta_T(i,p)-\frac{\theta(i)}{2}\right)-\sqrt{d^2(i,p)\left(\cos^2\left(\Delta_T(i,p)-\frac{\theta(i)}{2}\right)-1\right)+R_P^2}. \tag{13}$$

Once $r_{LIM}(i,p)$ is known, $P_{MAX}(i,p)$ is easily calculated from (9).

3.2. Setting the adequate Transmission Power

Now, for every primary p, we have $P_{MAX}(i,p)$. But since the transmitting node i has only one value of the transmission power it can use, the less interference prone, for the primary network, is $\min(P_{MAX}(i,p))$. By assuming a constant maximal transmission power P_{TMAX} that each node cannot exceed, the adequate transmission power for a transmitting node i is finally:

$$P_T(i)=\min\left(P_{TMAX},\{P_{MAX}(i,p)\forall p\in S_P\}\right). \tag{14}$$

4. Future Work

In this paper, we considered a protection circle of constant radius R_P surrounding each primary. Nodes were assumed to know this radius value in order to control their transmission power so as to keep minimal the aggregate interference to the primary network. Since every primary p omni-directionally broadcasts a small message with $I_{Ag}(p)$ as the payload, MANET nodes will regularly get an approximation of p's position which could vary over time and nodes position, as shown on Figure 4.

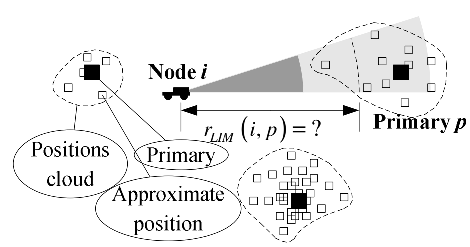

Figure 4: *Approximate primary position.*

But this growing random sample, gathered individually at each node, now gives rise to new interesting and challenging topics.

The choice of R_P undoubtedly has an impact on the MANET communication performance, as well as the aggregate interference to the primary network. If R_P is too small, nodes may have better communication to the detriment of primary's QoS. On the other hand, if R_P is too large, nodes may ineffectively lower their transmission power, decreasing the MANET performance, although the primary's QoS is even far from being critical. The environment surely has to be considered when choosing the value of R_P. For example, the imprecision on gathered primaries positions could be different for an underground mine than for an outdoor open area, mainly because of the hardly predictable radio wave propagation [1]. Allowing each node to adapt the value of R_P for each primary, thus not making it constant anymore, is an unprecedented research project on its own.

5. Conclusion

The deployment of a smart-antennas-equipped MANET in an underground mine promises good benefits, especially when nodes are not always allowed to transmit towards specific areas. The presence of a primary network, already using the same frequency band of the MANET acting as a secondary network, gives new challenges to MANETS and power control. The proposed algorithm, with its power control mechanism, can be applied to many already existing protocols. Future work will focus on developing a neighbor discovery algorithm for a smart-antennas-equipped cognitive MANET, such that nodes will have to discover themselves while using the presented power control to reduce the aggregate interference to a primary network, which could be very harmful for the legacy network QoS. Also, coping with the imprecision in getting the distance and direction of a primary, with the reception of broadcasted small messages, merits further investigation. Considering a primary network using directional antennas as well as the MANET could be a very challenging research project.

Acknowledgment

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