Reliable power control for secondary users based on distributed measurements

Gitte Vanwinckelen*, Martijn Van Otterlo*, Kurt Driessens† and Sofie Pollin‡

*Department of Computer Science
Katholieke Universiteit Leuven, Belgium
Email: gitte.vanwinckelen@cs.kuleuven.be, martijn.vanotterlo@cs.kuleuven.be
†Department of Knowledge Engineering
Maastricht University, Netherlands
Email: kurt.driessens@maastrichtuniversity.nl
‡Interuniversity Micro-Electronics Center
Leuven, Belgium
Email: pollins@imec.be

Abstract—**An important aspect of spectrum sharing is reliable protection of licensed, primary, users from interference by unlicensed, secondary, users. In this paper we investigate the reliability of the iterative power adjustment algorithm proposed by Pollin, Adams and Bahai (2008). The goal of this transmission power control algorithm is to allow a static secondary transmitter to maximize its power without interfering with primary users. A distributed flooding algorithm is used to detect primary users and estimate the distance to the primary propagation contour. The secondary transmitter makes a local channel estimation with a moving least squares algorithm to average out noise. The metric used to estimate interference is the propagation contour-contour distance between the secondary and primary transmitters. In our first contribution we investigate the reliability of this metric by computing the location probability, a new FCC proposed metric for configuring Digital Terrestrial Television networks. We show that the propagation contour-contour distance is correlated with the location probability. In a second contribution we make the flooding algorithm more cost efficient by reducing communication. We then study the influence of the number of flooding messages on the performance of the iterative power adjustment algorithm in terms of location probability and number of iterations.**

Time, space and frequency spectrum are three important shared resources in wireless communications. But these resources are limited and with the continuous development of new wireless technologies and the increasing number of coexisting wireless networks there is a need to share these resources more efficiently. In this paper we focus on sharing space by transmission power control (TPC). In a wireless network we can make a distinction between *primary* and *secondary* users. Primary users are licensed and have priority to use the spectrum. Secondary users are not licensed and are only allowed to use the spectrum where it is not needed by the primary users and the interference that they cause to the primary users has to be minimized. In TPC, the goal is to make the transmission range of a secondary transmitter as large as possible while causing as little interference as possible to any primary users.

To find spectrum holes and compute its optimal transmission range, a secondary transmitter needs knowledge of the prop-agation conditions and the presence of primary users. In the literature three general approaches exist to find spectrum holes. The first approach is *spectrum sensing* [1], [2]. A problem here are the high sensitivity requirements to detect all activity of the primary users and to overcome the hidden terminal problem. Studies conducted by both the Federal Communications Commission (FCC) and Electronic Communications Committee (ECC) have recently revealed serious doubts about the reliability of existing spectrum sensing solutions and have subsequently deferred from making these techniques an obligatory part of secondary use regulations. However, at the same time the FCC recognized the value of sensing for, for instance, the TV White Spaces in the following statement: "We continue to believe that spectrum sensing will continue to develop and improve. We anticipate that some form of spectrum sensing may very well be included in TV Band Devices [3]." In parallel to local sensing, other approaches are however needed to achieve a more reliable detection of spectrum.

Instead of local sensing, *cooperative* sensing can be used. Here the sensing results of multiple secondary users are combined to make a decision on the presence of a primary transmitter. A second approach to detect spectrum holes is *geolocation* [4]. In this approach a user consults a central database to determine which frequencies are available at his location. A third approach is the use of dedicated signals, *beacons*, to communicate the availability of frequencies [5].

In the work of Pollin, Adams and Bahai [6], an alternative approach to detect primary users is presented. A flooding algorithm is used to communicate the presence of primary transmitters to the rest of the network. This approach has some advantages. Like spectrum sensing, the approach is distributed and relies on field measurements. Therefore it does not require any additional infrastructure. Furthermore, responses to changes in the environment are quicker. Unlike spectrum sensing, no expensive high sensitivity sensing techniques are needed.

In this *iterative power adjustment* (IPA) algorithm, the

power of the secondary transmitter is iteratively adapted based on the estimated distance between the interference threshold contours of the primary transmitters and the secondary transmitter. The estimated distance between the contours is communicated with a flooding algorithm from the primary transmitters throughout the rest of the network. The assumption is that the secondary transmitter causes no interference if a minimum distance between the contours of the primary transmitters and the contour of the secondary transmitter is respected.

Our first contribution is to investigate the reliability of the IPA algorithm by looking at the *location probability*. In ECC report 159 [7], the location probability is defined as "The probability with which a Digital Terrestrial Television (DTT) receiver would operate correctly at a specific location; i.e. the probability with which the median wanted signal level is appropriately greater than a minimum required value". According to the report, the location probability is widely used in the planning of DTT networks to measure the quality of coverage of a transmitter. Because the location probability takes into account interference from secondary transmitters, we can use it to test the reliability of the computation of the optimal transmission power by the IPA algorithm. We look at a scenario were the goal is reliable coexistence of a primary and a secondary DTT transmitter and show that there is a correlation between the location probability and the propagation contour-contour distance.

In our second contribution we adapt the flooding step of the IPA algorithm to decrease the communication overhead. Besides the reduced overhead, this also implies a reduction of interference. We compare the performance of the original and the adapted IPA algorithm in terms of the number of iteration steps and the location probability. The algorithms are simulated in a two-dimensional environment that employs a general path loss model.

The paper is organized as follows. In Sec. I we give some preliminaries regarding the choice of the path loss model used in the simulations and the choice to use a flooding algorithm. Sec. II then explains the IPA algorithm, which consists of three components: Received power estimation, distance-to-contour flooding and path loss estimation. Here, we also discuss the path loss model used in the simulations. In Sec. III we study the reliability of the IPA algorithm in terms of the location probability. We relate the location probability to the propagation contour-contour distance metric used in the algorithm. Next, we propose the alternative distance-to-contour flooding algorithm and compare it with the original flooding algorithm in Sec. IV. We look at several performance metrics such as the number of forwarding users, location probability and number of iterations of the IPA algorithm. Conclusions are presented in Sec. V.

I. PRELIMINARIES

The goal of the IPA algorithm is to find the optimal transmission power of any secondary transmitter. The optimal transmission power maximizes the transmission range of the secondary transmitter while causing no interference to any primary users. To find this power, a secondary transmitter needs knowledge of the radio propagation conditions and the presence of any primary transmitters.

A. Local power variance

Radio propagation is typically modeled by a model consisting of three components: a distance dependent path loss trend, shadowing and fast fading. Shadow losses cause the received signal strength (RSS) to vary slowly in time and space around the distance dependent trend. Fast fading originates from multipath effects and causes the RSS to vary on a small scale [8]. Pollin, Adams and Bahai deduce from experiments that propagation conditions are difficult to model globally[1][6]. Therefore, the IPA algorithm does not rely on a global propagation model but uses only local RSS measurements.

B. Distance to contour flooding

To detect the primary users and compute the distance between the transmission range of a primary user and the secondary user, no expensive sensing techniques are used. Instead, a more cost efficient distance-to-contour (DTC) flooding algorithm is used. This algorithm uses a back-off timer to decrease the number of forwarded messages with respect to regular flooding [9]. With the DTC flooding algorithm, the number of forwarded messages is slightly larger than n, with n being the number of users in the network. In this paper we develop an alternative distance-to-contour flooding algorithm which decreases the number of forwarded messages. This adapted flooding algorithm, DTC2, is based on the polygon tiling algorithm proposed by Hur et. al. [10].

II. ITERATIVE POWER ADJUSTMENT ALGORITHM

A. Overview

We give an overview of the IPA algorithm in a situation with one primary and one secondary transmitter. However, the algorithm is also applicable in scenarios with multiple primary transmitters. When the RSS of a user is used in the algorithm, an estimate $\hat{RSS}$ is computed with a MLS algorithm to average out the noise due to fast fading. This procedure is discussed in section II-B.

First, receivers of the primary transmitters compute their $\hat{RSS}$ to find the users that define the interference threshold contour of the primary transmitter. Next, every user in the network is informed about his distance to the contour by means of the DTC flooding algorithm. DTC is discussed in section II-C. Based on the distance to the contour of the primary transmitter and a worst case path loss model, a secondary transmitter can now make a first estimate of its transmission

---

[1]In the measurement campaign of Pollin, Adams and Bahai [6] the RSS from an 802.11 antenna on top of Cory Hall at UC Berkeley is measured in the area. They make three observations from the measurements. First, there is no obvious relationship between the RSS and the distance between the transmitter and the receiver. Second, the measurements show that shadowing is an anisotropic effect. Last, fast fading causes the RSS measurements to be noisy.

power. This initial estimate can iteratively be made more accurate based on information about the propagation conditions between the secondary and primary transmitter. First, the new contour-contour distance is taken into account. Second, the path loss between the contour of the secondary and primary transmitter is estimated at the user that is closest to the primary transmitter and still within the transmission range of the secondary transmitter. We discuss the iterative adaptation of the transmission power in section II-D.

B. Local received power estimation

Reliable RSS estimates are needed for two reasons: To determine the interference threshold contours and to make accurate path loss estimations. The individual RSS measurements are noisy due to fast fading. In order to average out this noise, a MLS algorithm is used. This has the advantage that it does not rely on a global path loss model.

The MLS algorithm does not only take into account the RSS measurement of the user where the estimate is computed but also the measurements from the neighboring users. The size of the neighborhood is defined by a spatial weighting function (also called *kernel function*). Assume we want to determine the $R\hat{S}S$ of user N at position x_N. We search the coefficients $\mathbf{a}$ of a polynomial $\mathbf{p}$ by minimizing the weighted least squares function from equation 1. Polynomial $\mathbf{p}$ approximates the local RSS variations in the environment. To find $\mathbf{a}$, the local received power RSS_N of user N is taken into account together with the local received power RSS_i of the neighbors of N, with $i = 1..\#\text{Neighbors}$:

$$\hat{\mathbf{a}}_N = \arg\min_a \sum_i w_{Ni}(\mathbf{a}^T \mathbf{p}(\mathbf{x}_i) - \mathbf{RSS_i})^2$$

The local RSS measurements are weighted by w_{Nj} according to the distance from user N, as demonstrated here:

$$w_{Ni} = \begin{cases} (1 - r_{Ni}^2)^3 & \text{, if } r_{Ni} \leq 1 \\ 0 & \text{, otherwise} \end{cases}$$

r_{Ni} is the normalized distance between user N and i. The distance is normalized by the kernel width h as follows: $r_{Ni} = \frac{\|\mathbf{x}_N - \mathbf{x}_i\|}{h}$. From the coefficients $\hat{\mathbf{a}}_N$ we can compute $R\hat{S}S_N$ as:

$$R\hat{S}S_N = \hat{\mathbf{a}}_N^T \cdot \mathbf{p}(\mathbf{x}_N)$$

The MLS algorithm has two parameters: kernel width h and the polynomial order of $\mathbf{p}$. These parameters depend on the noise power and can be optimized with respect to the average squared error on $R\hat{S}S$. This is demonstrated in the work of Pollin, Adams and Bahai [6].

C. Distance to contour flooding

An efficient flooding algorithm based on the algorithm proposed by Ye, Chen, Lu and Zhang [9] is used to signal the presence of primary transmitters. The goal of the distance-to-contour flooding algorithm is to inform every user in the network about his distance to the contour of the primary user. A potential secondary transmitter can then determine the

position of the wireless user within its transmission range that is closest to the contour of the primary user. In the next step of the IPA algorithm the path loss estimate of this closest secondary user is used to improve the estimate of the optimal transmission power of the secondary transmitter.

The centralized version of the DTC algorithm uses a priority queue to keep track of all information. Consider a scenario with transmitter P and n wireless users. All users that receive P with a RSS larger than the interference contour threshold, RSS_{th}, are within the transmission range of P and are called *internal* users. The *footpoint* f_i of a user i with respect to P is defined as the internal user of P that is closest to i. The goal of the distance-to-contour algorithm is to inform all users about their footpoint f and the distance d to this footpoint.

1) During initialization all internal users of P are added to a priority queue. The footpoint of an internal user is the position of the user himself, $f_i = x_i$, and thus $d(i, f_i) = 0$. For all other users $d = \infty$.
2) The user with the smallest distance, user N, is taken from the queue. If more users share this smallest distance, one is randomly selected
3) User N now informs his one-hop neighbors about his footpoint $f_N = x_A$. Based on this information the neighbors of N update their footpoint and distance as follows: consider user M which is a neighbor of N. The footpoint of M is $f_M = x_B$ with $d(x_M, x_B)$. There are two possibilities:
   a) If $d(x_M, x_A) < d(x_M, x_B)$ then $f_M \leftarrow x_A$ and $d(M, f_M) \leftarrow d(x_M, x_A)$, and M is added to the queue.
   b) If $d(x_M, x_A) \geq d(x_M, x_B)$ then f_M does not change and M is not added to the queue.
4) When all the neighbors of N are updated, N is removed from the queue. The next user is now taken from the queue and all his neighbors are updated.
5) The process is repeated until the queue is empty

To minimize the number of forwarding messages in the distance-to-contour flooding algorithm, the order in which users update their neighbors depends on their distance from P. In the centralized algorithm this is implemented by using a priority queue. In a practical scenario where users only communicate with their one-hop neighbors a priority queue cannot be used. The algorithm is made distributed by implementing the distance dependence with a back-off timer.

Ideally, the time in which the network is updated equals $CW \cdot h$, with h the communication range. The number of messages equals n, with n the number of users in the network. In a practical scenario the update time and number of messages will be larger due to two reasons:

- Retransmissions are necessary because of collisions.
- It is possible that a user starts updating his neighbors before he has obtained his closest footpoint. Wrong information is propagated to the neighbors and the user will have to update his neighbors a second time once he obtained his correct footpoint. We say the neighbors are
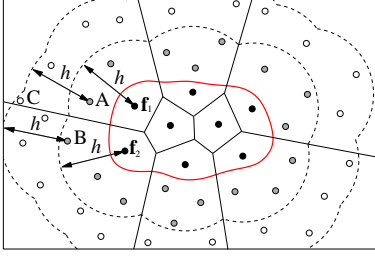
Fig. 1. Users with the same footpoint are grouped together by a Voronoi Tiling. User C has footpoint f_1 and it lies in the transmission range of both users A and B. If the backoff timer of B goes off before the back-off timer of A, user C gets updated first by user B and it will incorrectly store f_2 as its footpoint. After user C is updated by user B, it starts a back-off timer to update its neighbors. However, when the back-off timer of user A goes off, C receives its correct footpoint f_1. If C has already updated its neighbors before it receives the update from A, user C will have to update its neighbors a second time. Figure from Pollin et.al. [6]

misclassified. This is illustrated in Fig. 1.

D. Path loss estimation

When every user knows his distance to the contour of the primary transmitter P, a secondary transmitter S can estimate its optimal transmission power, power_S, based on a local path loss estimate $\hat{PL}$ computed at the internal user of S that is closest to the primary contour, user i_{cl}. First, parameters α and β of a path loss model are computed with a weighted least squares fit at i_{cl}. All the neighbors, j, within the kernel width h around i_{cl} are taken into account. This is shown in equation 1. Parameter α models the distance-dependent trend and β consists of shadow and antenna losses. $d(S,j)$ is the distance between the transmitter S and a receiving user j. Next, the power of S is computed as the maximal interference power plus the estimated path loss between S and the contour of the primary transmitter. This is shown in equations 2 and 3.

$$\hat{\alpha}_i, \hat{\beta}_i = \tag{1}$$
$$\arg\min_{\alpha,\beta} \sum_j w_{ij}(\alpha 10 \log_{10} d(S,j) + \beta - \text{PL}_j)^2$$

$$\hat{\text{PL}}(S, f_{i_{cl}}) = \hat{\alpha} 10 \log_{10} d(S, f_{i_{cl}}) + \hat{\beta} \tag{2}$$

$$\hat{\text{power}}_S = RSS_{th} + \hat{\text{PL}}(S, f_{i_{cl}}) \tag{3}$$

Note that it is hypothesized that the local path loss estimation at i_{cl} gives information about the long range path loss between the primary and secondary transmitter. However, extrapolation over a long range and the presence of outliers can invalidate this hypothesis. We investigated a number of more complex approaches to solve this problem but they did not lead to a useful result. Further investigation is needed.

E. Path loss model

The IPA algorithm is tested in a simulated two-dimensional environment. In this section we present the path loss model used to simulate radio propagation conditions. The path loss PL consists of four components which we discuss below: A

distance dependent trend, antenna losses, shadowing and fast fading:

$$PL = 10\alpha \log(d) + \gamma + L_S + X_\sigma$$

First, path loss increases exponentially with the distance d from the transmitter. The rate of increase is modeled by parameter α. Second, antenna losses are modeled by parameter γ. Third, shadow losses, L_S, are modeled by placing buildings in the scenario as explained in the work of Pollin, Adams and Bahai [6]. Last, fast fading is modeled as Gaussian noise, X_σ, with variance σ^2. Pollin, Adams and Bahai showed that $\sigma^2 = 4$ is a realistic value for fast fading, thus this value is used in our simulations [6]. However, the exact parameters of the path loss model are not important because the IPA algorithm only makes use of local path loss measurements.

III. RELIABILITY OF THE IPA ALGORITHM IN TERMS OF LOCATION PROBABILITY

To determine the maximum transmission power of a secondary transmitter and ensure protection of the primary users, knowledge of the path propagation characteristics is needed. Examples of these characteristics are: the distances between the secondary transmitter and any primary transmitters, terrain shape and the relative antenna discrimination. The latter two characteristics determine the path loss PL. Although the characteristics are not known directly by the secondary transmitter, they can be estimated with the IPA algorithm. The distances between the secondary and primary transmitters can be computed with the distance-to-contour flooding algorithm and a local estimation of the path loss is computed with a MLS algorithm. In this section we investigate the reliability of the estimation of the path propagation characteristics by looking at the location probability.

A. Location probability[2]

The location probability q is defined as the probability with which a primary DTT receiver would operate correctly at a specific location, or gridpoint; i.e., the probability with which the median wanted signal level P_P is appropriately greater then a minimum required value; i.e.,

$$q = Pr\{P_P \geq P_{P,min} + \sum_{i=1}^{K} r_{S,i} P_{S,i}\} = Pr\{P_P \geq S\}$$

In this formula, $P_{P,min}$ is the primary receiver's (noise-limited) reference sensitivity level [3], $P_{S,i}$ is the received power of the ith unwanted, secondary, DTT signal and $r_{S,i}$ is the DTT-to-DTT protection ratio for the ith DTT transmitter; i.e., the minimum ratio of the wanted signal power and the interference signal power necessary for correct operation of the receiver. In the path loss model used in the simulations, the RSS at a gridpoint is a Gaussian variable were the mean m is determined by the distance from the transmitter, antenna

---

[2]In this section we follow the description given in ECC report 159 [7].

[3]The reference sensitivity level of a receiver is the minimum wanted signal power for which the receiver can operate correctly in a noise-limited environment.
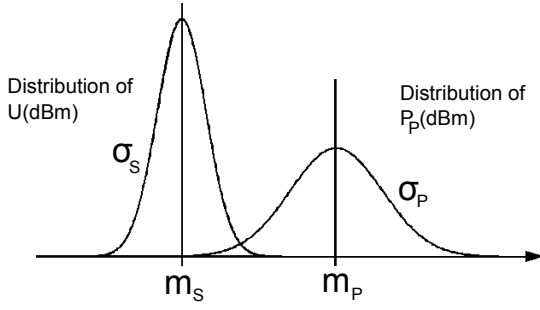
Fig. 2. The Gaussian distributions of the power of a secondary transmitter S and a primary transmitter P at one gridpoint. To compute the location probability at a location, we compute $Pr\{P_P \geq S\}$. Figure from [7]

TABLE I
RELIABILITY OF THE IPA ALGORITHM IN TERMS OF THE LOCATION
PROBABILITY AND OVERLAP OF THE INTERFERENCE THRESHOLD
CONTOURS FOR THREE DIFFERENT SCENARIOS.

		Δ (%)	contour overlap (%) PU
example 1	update 1	7	0
(2000 nodes)	update 2	7	0
	update 3	7.1	0
example 2	update 1	8	0
(1500 nodes)	update 2	9.1	0.3
	update 1	7.9	0
example 2	update 2	7.9	0
(1800 nodes)	update 3	7.9	0
	update 4	10.6	0

losses and shadowing. The variance σ^2 is determined by the amount of fast fading. Consider a gridpoint were a receiver senses the primary and secondary transmitter. We compute $Pr\{P_P \geq S\}$ at this gridpoint with Eq. 4. as illustrated in Fig. 2.

$$q = 1 - \frac{1}{2}\text{erfc}\{\frac{1}{\sqrt{2}}\frac{m_{S(dBm)} - m_{U(dBm)}}{\sqrt{\sigma_S^2 + \sigma_U^2}}\} \qquad (4)$$

B. Simulation results

A simulation of the IPA algorithm is shown in Fig. 3. The effect of the secondary transmitter on the location probability of the primary transmitter for this simulation is illustrated by the results for example 2 in Tab. I. The table also shows the results for two other simulations.

In the second column of the table, Δ indicates the decrease of the area, A (*with SU*), of the 95% location probability contour of the primary transmitter in comparison with the area of the contour when there is no interference from a secondary transmitter, A (*no SU*), as shown in Eq. 5. The decrease is indicated for every iteration of the IPA algorithm.

$$\Delta = \frac{A(no\ SU) - A(with\ SU)}{A(no\ SU)} \qquad (5)$$

The third column shows the overlap of the interference threshold contours of the primary and the secondary transmitter as computed by the IPA algorithm. The overlap is expressed as the percentage of the area of the primary transmitter's contour that is overlapped by the contour of the secondary transmitter.

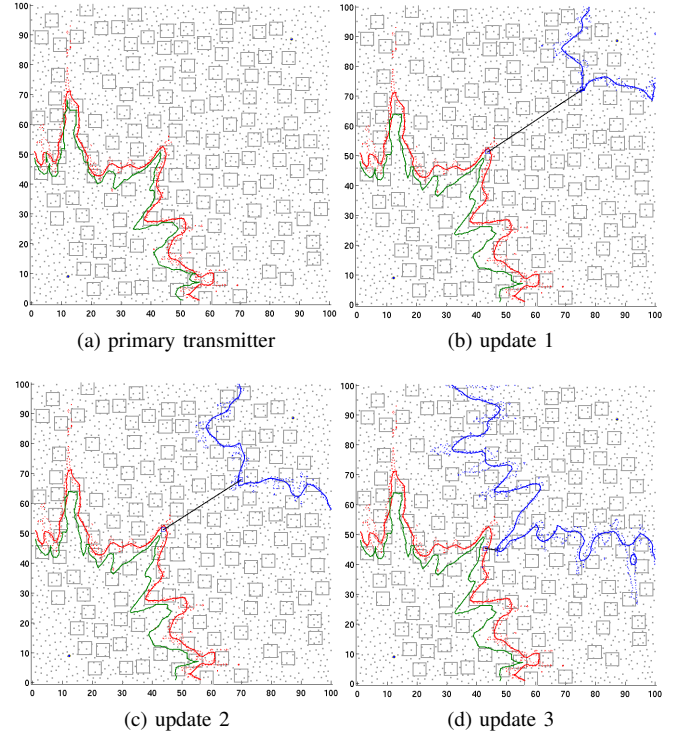(a) primary transmitter

(b) update 1

(c) update 2

(d) update 3

Fig. 3. Demonstration of the IPA algorithm for example 2 from Tab. I. A primary transmitter is present in the lower left corner of the scenario and its interference threshold contour is indicated in red. The 95% location probability contour is indicated in green. In the upper right corner a secondary transmitter is present with the interference contour indicated in blue.
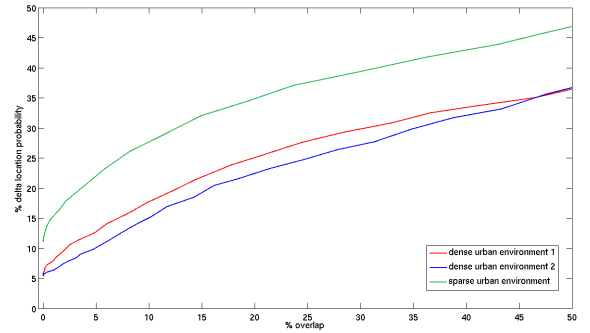

Fig. 4. Reduction of the 95% location probability contour in function of the overlap of the primary and secondary contour computed by the IPA algorithm.

The simulations from Tab. I show that the presence of a secondary transmitter reduces the location probability with 7 to 10%. The biggest reduction of the location probability is caused by the presence of a secondary transmitter and not by the increase in power as computed by the IPA algorithm. The reliability of the IPA algorithm is confirmed by Fig. 4. This figure shows that there is a relationship between the interference threshold contours computed by the IPA algorithm and the location probability. This justifies the use of the propagation contour-contour distance computed by the IPA algorithm as a metric for interference.

IV. REDUNDANCY REDUCTION OF DISTANCE-TO-CONTOUR FLOODING

Broadcasting information from a source user to the rest of the network with regular flooding causes problems such as redundancy, contention and collisions [11]. Redundant messages also unnecessarily increase the interference. The distance-to-contour flooding algorithm reduces the number of flooding messages by using a back-off timer to impose an ordering on the transmitting users. For a network with n users, the number of flooding messages is approximately equal to n. In this section we propose an alternative to DTC that reduces the number of transmitting users further. From now on, we refer to the adapted distance-to-contour flooding algorithm as the DTC2 flooding algorithm.

Flooding algorithms can be divided into three categories based on the amount of information users needs from their neighbors [12]. The first category are the flooding algorithms that require no information, for example *regular* flooding and *probabilistic* flooding. Algorithms from the second category reduce redundant transmissions by having every user select only a subset of its neighbors to forward a message. For this, a user needs information about his *one-hop* (direct) neighbors. DTC2 belongs to this category. Another example can be found in the work of Liu et.al. [12]. The third category contains algorithms that use information about neighbors that are *two hops* or more away [13].

A. Ideal network topology

DTC2 selects the forwarding neighbors according to the selection criterium proposed by Hur et. al. [10]. The idea is to approximate an ideal network topology where the overlapping area of the users' transmission ranges is minimized. Fig. 5a and Fig. 5b show the ideal topology for a user with respectively three and four neighbors and Fig. 5c and Fig. 5d show the resulting hexagonal and square tiling topology in a network. We chose to investigate the square tiling topology from Fig. 5b because there is less redundancy in the communication when a user only forwards to four neighbors instead of six neighbors in the hexagonal tiling topology.

In a real network the users are deployed randomly and previous discussed topologies do not occur, so the criterium to select forwarding neighbors is to choose the neighbors located closest to the ideal positions. By reducing the number of forwarding neighbors, the number of transmissions and collisions is also reduced. By choosing the users closest to the ideal positions we aim to have all users in the network receive updates. We express this in terms of the *delivery ratio*, which is the ratio of the number of users that receive flooding messages to the total number of users in the network.

B. Forwarding user selection

The procedure to select forwarding neighbors is described by Hur et. al. [10] as follows:

We assume every user knows his position by GPS or a positioning algorithm. Consider user s from Fig. 6 with
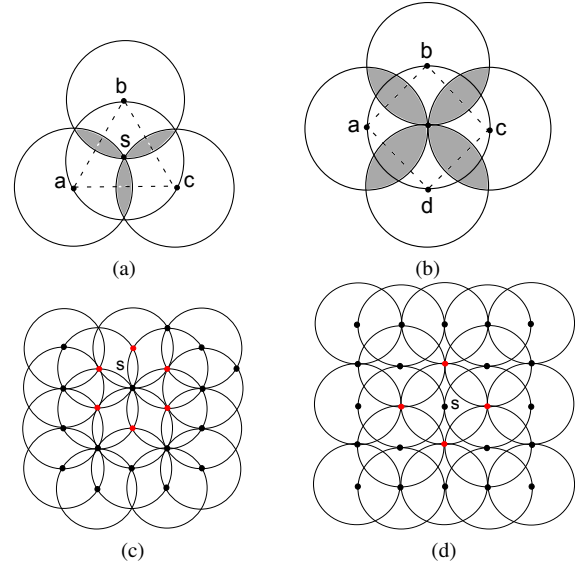

Fig. 5. Fig. 5a and Fig. 5b show the ideal topology for a user with respectively three and four neighbors. This topology minimizes the overlapping areas of the transmission ranges. Fig. 5c and Fig. 5d show the resulting network topologies for respectively three and four neighbors. Figures by Hur et. al. [10]
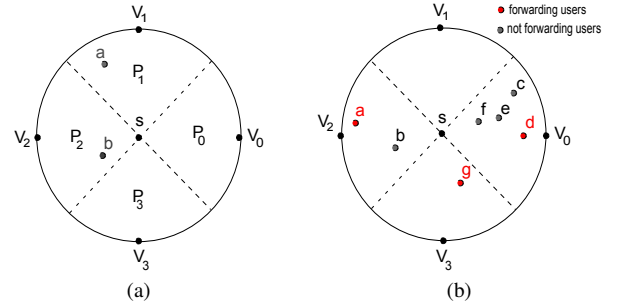

Fig. 6. Fig. 6a demonstrates the partitioning of the transmission range of user s. Fig. 6b shows an example of which users are selected as forwarding neighbors. Figures by Hur et. al. [10]

coördinates (x_S, y_S). Partitions P_0, P_1, P_2 and P_3 divide the transmission range of s in four as illustrated in Fig. 6a.

With every partition P_i there is one vertex V_i associated, with $0 \leq i \leq 3$. These vertices indicate the positions of the four forwarding neighbors in case of an ideal square tiling topology. A user determines the forwarding neighbors as follows: For each partition P_i the neighbor closest to V_i is selected. If the partition is empty, no neighbor is selected. The selection is illustrated in Fig. 6b.

Whereas in step three of the DTC algorithm, all the neighbors of a user forward their footpoint, in DTC2 only a subset of forwarding neighbors is selected. We consider again a scenario with transmitter P and n wireless users and describe this third step of DTC2 in which a user N updates his one-hop neighbors about his footpoint $f_N = x_A$. Based on this information the neighbors of N update their footpoint and distance in the same way as in the DTC flooding algorithm. user N also computes the set of forwarding neighbors $F(N)$ as discussed above.

Consider the following example of the update and forwarding process for a neighbor of user M that is a neighbor of user

N. User N has footpoint $f_N = x_A$ and distance $d(x_N, x_A)$ to this footpoint. User M has footpoint $f_M = x_B$ and distance $d(x_M, x_B)$ to this footpoint. There are two possibilities:

1) If $d(x_M, x_A) < d(x_M, x_B)$, then $f_j \leftarrow x_A$ and $d(x_M, f_M) \leftarrow d(x_M, x_B)$.
   - If user $M \notin F(N)$, M is not added to the queue.
   - Otherwise, M is added to the queue.

2) If $d(x_M, x_A) \geq d(x_M, x_B)$, then the footpoint of M does not change and user M is not added to the queue, independent of whether it is a member of $F(N)$.

C. Simulation results

In this section we compare some performance metrics for simulations of the IPA algorithm with both DTC and DTC2. We look at the communication redundancy in terms of the size of the transmission range (also called communication range) and investigate whether using DTC2 has an influence on the reliability of the computation of the power of the secondary transmitter. The results are averages over three simulations. For DTC, all the users forward information and the transmission range has no influence. For DTC2, an increase in the transmission range reduces the percentage of forwarding users, as shown in Fig. 7a. This is because the number of forwarding neighbors per user is always maximum. However, in comparison with DTC, extra communication is needed to inform a user about the positions of his neighbors. A user needs this information to determine the forwarding set of neighbors.

For a network with n users, the number of updates for the DTC algorithm is slightly larger than n because of collisions and misclassified users, as explained in section II-C. Fig. 7c shows the percentage of misclassified users and the number of updates in function of the kernel width. In the simulated network, the users are randomly distributed and the topology is not ideal. Therefore not all users receive their correct footpoint when using DTC2 and the number of misclassified users is slightly larger than for DTC. However, the incorrect footpoint is always received from a user within the distance of a one-hop neighbor so the error is not large. Fig. 7d shows that the average error is never larger than 3%. It seems that as the transmission range increases, the average error also slightly increases, but this should be investigated further. When the delivery ratio is smaller than one, because the transmission range is too small, the average error increases as shown in Fig. 7d.

Last, Fig. 7b shows that using DTC2 does not have an effect on the performance of the IPA algorithm. The size of the transmission range also has no influence. We see no difference in the size of the overlap of the contours or the reduction of the location probability when using DTC or DTC2, or by varying the transmission range. We also investigated that the number of iterations for the IPA algorithm to converge lies between three and seven iterations, regardless of whether DTC or DTC2 is used.

V. Conclusions and future work

We investigated the reliability of the IPA algorithm proposed by Pollin, Adams and Bahai [6] in terms of location probability. This algorithm allows a static secondary transmitter to maximize its power without interfering with primary users. As an interference metric, the propagation contour-contour distance between the secondary and primary transmitter is used. Our simulations showed that this metric is correlated with the location probability and that the IPA algorithm makes a reliable estimation of the maximum allowed power of a secondary transmitter. To detect primary users and estimate the distance to the primary propagation contour, a distributed flooding algorithm, DTC, is used. To reduce the redundancy in communication, we proposed the DTC2 flooding algorithm that selects a subset of forwarding users. The algorithm reduces the number of transmissions at the cost of two things. First, we assume every user has a limited computation power available to select a subset of forwarding neighbors. However, this assumption is often valid in ad-hoc sensor networks because it is necessary for robust and scalable communication algorithms (Referentie!). Second, for a large delivery ratio DTC2 is best used in a network with a high user density.

There are a number of options to improve our current algorithms. First, there is extensive literature on efficient flooding algorithms. Next to DTC2, we propose to investigate other cost efficient flooding algorithms and study their effect on the reliability of the IPA algorithm. Second, we want to investigate the robustness of the path loss estimation step to outliers and possibly improve this robustness. Last, the algorithm can be extended to also handle moving secondary transmitters.

VI. Acknowledgments

References

[1] A. Ghasemi and E. Sousa, "Spectrum sensing in cognitive radio networks: requirements, challenges and design trade-offs," *Communications Magazine, IEEE*, vol. 46, no. 4, pp. 32 –39, 2008.

[2] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *Communications Surveys Tutorials, IEEE*, vol. 11, no. 1, pp. 116 –130, 2009.

[3] "Second memorandum opinion and order. in the matter of unlicensed operation in the tv broadcast bands, additional spectrum for unlicensed devices below 900 MHz and in the 3 GHz band," Federal Communications Commission, Document 10-174, 23 Sep. 2010.

[4] D. Gurney, G. Buchwald, L. Ecklund, S. Kuffner, and J. Grosspietsch, "Geo-location database techniques for incumbent protection in the TV white space," in *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, 2008, pp. 1 –9.

[5] G. Buchwald, S. Kuffner, L. Ecklund, M. Brown, and E. Callaway, "The design and operation of the ieee 802.22.1 disabling beacon for the protection of tv whitespace incumbents," in *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, 2008, pp. 1 –6.

[6] S. Pollin, B. Adams, and A. Bahai, "Spatial reuse for practical scenarios: Iterative power adjustment from distributed contour estimation and propagation," *Communications, 2008. ICC '08. IEEE International Conference on*, pp. 2655 –2661, May 2008.

[7] "Technical and operational requirements for the possible operation of cognitive radio systems in the 'white spaces' of the frequency band 470-790 MHz," CEPT ECC Report 159, draft SE43(10)126-Annex 3, 2010, see http://www.cept.org/764D6AAF-6354-49CD-B981-FA4B46AF493E.W5Doc.

[8] T. Rappaport, *Wireless communications: Principles and practice*, 2nd ed. Prentice Hall, 2002, ch. 3, pp. 69–138.

[9] F. Ye, A. Chen, S. Lu, and L. Zhang, "A scalable solution to minimum cost forwarding in large sensor networks," *Computer Communications and Networks, 2001. Proceedings. Tenth International Conference on*, pp. 304 –309, 2001.

[10] I. Hur, T. D. Le, and H. Choo, "Efficient flooding scheme based on regular polygonal tiling in wireless ad hoc networks," *Advanced Communication Technology, 2009. ICACT 2009. 11th International Conference on*, vol. 01, pp. 810 –814, Feb. 2009.

[11] Y.-C. Tseng, S.-Y. Ni, and E.-Y. Shih, "Adaptive approaches to relieving broadcast storms in a wireless multihop mobile ad hoc network," in *Distributed Computing Systems, 2001. 21st International Conference on.*, Apr. 2001, pp. 481 –488.

[12] H. Liu, X. Jia, P.-J. Wan, X. Liu, and F. Yao, "A distributed and efficient flooding scheme using 1-hop information in mobile ad hoc networks," *Parallel and Distributed Systems, IEEE Transactions on*, vol. 18, no. 5, pp. 658 –671, May 2007.

[13] A. Qayyum, L. Viennot, and A. Laouiti, "Multipoint relaying for flooding broadcast messages in mobile wireless networks," in *System Sciences, 2002. HICSS. Proceedings of the 35th Annual Hawaii International Conference on*, 2002, pp. 3866 – 3875.
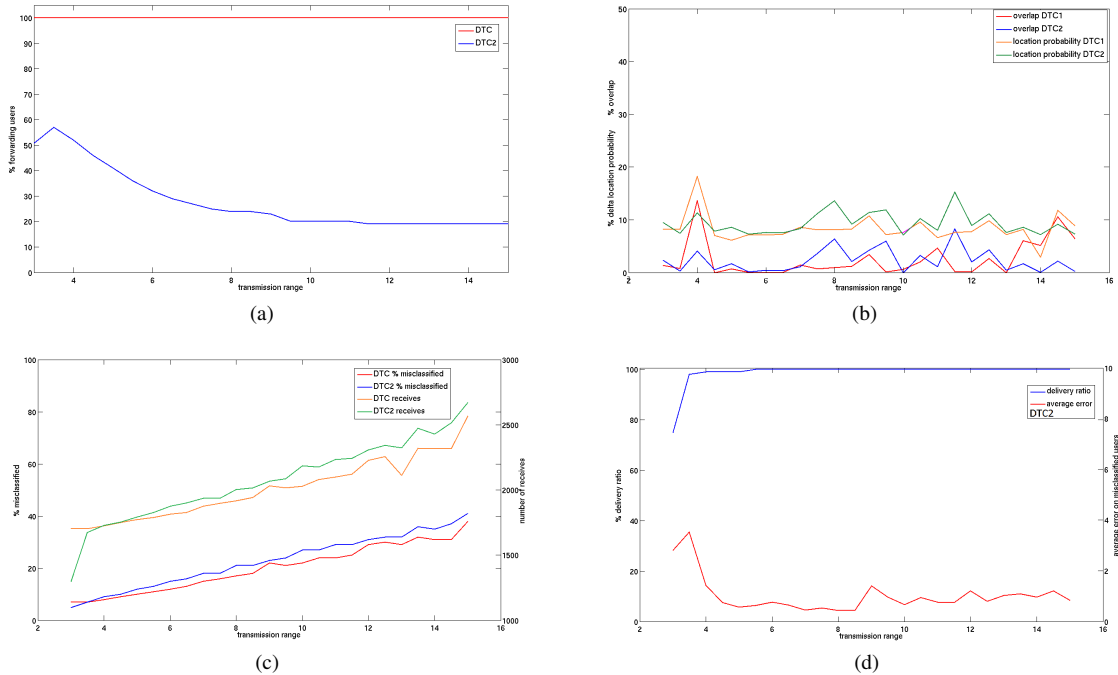
(a)

(b)

(c)

(d)

Fig. 7.   Fig. 7a: The percentage of forwarding users for DTC2 in comparison with the number of forwarding users for DTC. Fig. 7b: Percentage overlap of the primary contour by the secondary contour together with the percentage reduction of the 95% location probability contour of the primary transmitter in comparison with the absence of a secondary transmitter. Fig. 7c: Percentage of misclassified users and number of receives (or updates) for DTC and DTC2. Fig. 7d: The average error on the distance to footpoint for the DTC2 algorithm together with the delivery ratio.