Recovery Using Backup Channels in Channel-Hopping Cognitive Networks

Jelena Mišić and Vojislav B. Mišić
Ryerson University, Toronto, ON, Canada M5B 2K3

***Abstract*—When a channel-hopping cognitive network experiences a collision with primary user transmission, it may re-form the network by repeating the network formation (rendezvous) procedure, which is costly and time-consuming, or attempt to recover by re-establishing operation on an idle channel from a predefined backup set. In this paper we analyze a practical recovery mechanism implemented atop the transmission tax-based MAC protocol. The recovery mechanism uses a list of backup channels obtained from sensing data. We investigate the performance of the mechanism and show that a small number of backup channels suffices to ensure speedy and reliable recovery.**

I. INTRODUCTION

One of the main obstacles to uninterrupted operation of cognitive wireless ad hoc networks in the unpredictable activity of licensed primary users [2]. Avoidance of interference to and (more importantly) from primary user activity may be accomplished through channel hopping [7] in which secondary users form piconets that switch channels according to a common hopping sequence, which must be dynamically adapted to primary user activity. Collisions caused by primary user activity are still possible, in which case the cognitive piconet must re-form using the designated piconet formation (rendezvous) protocol [6]. While simple to implement, this solution suffers from long periods of inactivity and, thus, should be used as a last resort only. Instead, the first response to a collision should be an attempt to re-convene the piconet at a different channel and continue its operation – in other words, a recovery should be attempted.

However, recovery is among the problems that 'necessitate a different approach from the classical ad hoc networks' [1], which is probably the reason why it has not received sufficient attention. Even the few MAC protocols that include recovery– e.g., the approach presented in [8] – rely on the presence of a common control channel (CCC) to handle collisions and other interruptions [9]. While simple and elegant, this solution is not readily applicable in practice due to the difficulties in ensuring that the CCC is always available and interference-free [3].

In this paper we describe a mechanism for fast recovery that uses a list of backup channels to be used in case of a collision, and analyze its performance. The concept of backup channels was described in [4], but without specific details on the selection and use of such channels. In our proposal, the list of backup channels is regularly updated using the information about channels' state obtained by sensing and broadcast to all the nodes in the piconet. The mechanism is implemented atop the transmission tax-based MAC protocol [16], which is one of the few MAC protocols to integrate regular operation of a piconet (i.e., data transmission and reception, and bandwidth allocation) with sensing activities that aim to ensure smooth piconet operation in an environment with unpredictable primary user activity. A promising approach based on dynamic compressive sensing in a heterogeneous evironment was recently proposed [17].

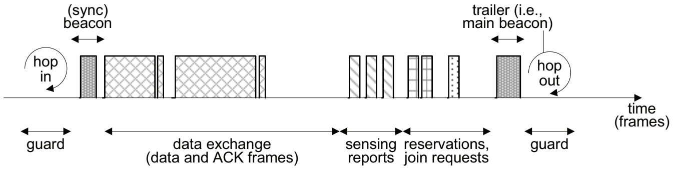


Fig. 1. Superframe and its periods.

The paper is organized as follows: Section II provides a brief description of the MAC protocol and the extensions necessary to enable and attempt recovery in case of a collision with a transmission of a primary user. Section III presents the analytical model of the recovery process, followed by performance results in Section IV. Finally, Section V concludes the paper and highlights some future research.

II. MAC AND RECOVERY PROTOCOLS

The CPAN uses a transmission tax protocol similar to our earlier proposals in [12]. In this protocol, time is slotted into unit slots and organized in superframes, as shown in Fig. 1, each of which occurs on a distinct channel. For convenience, we assume that the superframe contains s_f unit slots, Δ of which are reserved for administrative purposes. More details on the protocol can be found in [16].

The label comes from the requirement that nodes 'pay' for data transmission by obligatory spectrum sensing for a certain period of time, as determined by the penalty coefficient k_p [16]. A sensing node independently selects which channels it will sense and sends the results back to the coordinator which compiles and updates a list of idle and busy channels—the channel map—and decides on the channel to be used for the next hop. We assume that sensing nodes report back in each of the k_p superframes which allows the coordinator to have access to most recent sensing results but also allows the sensing nodes to stay synchronized to the CPAN hopping sequence.

The main beacon includes bandwidth allocation for previously received transmission requests and the next-hop channel.

For purposes of efficient rendezvous procedure [14], the trailer is implemented as a trailer, i.e., it is sent at the end of the superframe. Another short beacon frame is sent at the beginning of the superframe to facilitate recovery in case of a collision.

Collisions occur in two scenarios.First, the CPAN may hop onto a channel which is thought to be idle but is, in fact, active; we will refer to this event as a type 1 collision. Second, the primary user may also become active on the channel during an ongoing superframe; this is referred to as type 2 collision.

An ordinary node will detect a collision via a missing trailer frame; it should then switch to a suitable backup channel at a predefined time. Intuitively, the switch to a backup channel should be performed as soon as a collision is detected, which may occur before the expected trailer – perhaps a scheduled transmission or an ACK packet that has been explicitly requested have not been received. However, not all nodes will notice the onset of primary user activity at the same time: some nodes may have been absent on sensing duty, while others that have no traffic and no sensing duty may have temporarily switched off their radios to conserve energy. As the result, any attempt to re-synchronize the CPAN must be undertaken only at a time which is prescribed in advance.

As for the backup channel, it must be announced as an alternative to the ‘regular’ next channel in each superframe, so that all the nodes know where to go in case of a collision. This may be achieved by having the coordinator announce in the trailer not just the next channel to hop but a list of, say, l backup channels (which may easily be compiler from the coordinator’s channel map.) Once the nodes detect a collision, all they have to do is hop to the next backup channel from the list and wait there for the beacon frame. If the new channel is busy and the recovery does not succeed, another candidate channel is selected, and the procedure is repeated.

However, even this approach can’t solve all problems. Namely, the coordinator does not listen to the channel while transmitting the beacon or the trailer, hence it can’t detect a collision via a missing beacon or trailer. The solution is, then, to have the coordinator perform a quick sensing of the working channel at the beginning of the superframe, immediately upon emitting the beacon, and again upon emitting the trailer. Additional sensing does incur an extra delay, since the coordinator has to switch to reception and then sense the channel, but this is a small price to pay for the ability to keep the CPAN synchronized. Moreover, the guard interval during which the nodes hop to the next channel must be set to a large enough value anyway, because nodes with different hardware might need different time to perform the switch.

Since sensing is not performed during recovery, the information about backup channels is becoming more and more obsolete in the process (which means that the probability that a backup channel will not be idle increases with each new attempt), there is no need to keep the superframe duration within its normal bounds. (There is no data transmission either.) Instead, a predefined short superframe should be used until the recovery succeeds.

When all channels from the backup list sent in the last correctly received trailer have been visited, failure is declared and the piconet must undertake the rendezvous (discovery) procedure [14].

III. MODELING THE RECOVERY PROCESS

Let us assume that the durations of active and idle times on a channel, T_a and T_i, follow random probability distributions with the probability density functions (pdf’s) $t_a(x)$ and $t_i(x)$, respectively. As active and idle times alternate, the total cycle time on the channel will have the probability density function $t(x) = t_i(x) * t_a(x)$. Then, the probability that the channel is busy or idle can be calculated as $p_{on} = \frac{\overline{T_a}}{\overline{T_a} + \overline{T_i}}$ and $p_{off} = 1 - p_{on}$; average cycle time will be $\overline{T_{cyc}} = \overline{T_a} + \overline{T_i}$.

The process that counts cycles of primary source started with the onset of idle channel period on some channel σ is a renewal process, i.e., a random process which counts the number of some general cycles where cycle durations X_i, are i.i.d. nonnegative random variables [5]. The beginning of new cycle period is a renewal point at which a new probabilistic replica of the original renewal process starts. Consider the situation where the node visits the target channel when the channel is idle, at the time τ relative to the renewal point. According to renewal theory, $\tau = T_{i,-}$ is referred to as deficit (elapsed) idle time, while $T_i - \tau = T_{i,+}$ is referred to as residual (excess) idle time, both with respect to that particular channel. Deficit idle channel time has the probability distribution function (PDF) defined as $A(x) = P(\tau \leq x)$, while its pdf is $a(x) = \frac{dA(x)}{dx}$. Using the probability $P(T_i > x) = T_i^c(x) = \int_{y=x}^{\infty} t_i(y)dy$, we can calculate the PDF $A(x)$ and pdf $a(x)$ of the deficit idle time as

$$A(x) = \frac{1}{\overline{T_i}} \int_0^x T_i^c(y)dy \qquad (1)$$

$$a(x) = \frac{d}{dx} A(x) = \frac{T_i^c(x)}{\overline{T_i}} \qquad (2)$$

The process that counts the number of sensing events on channel σ is also a renewal process since time periods between two consecutive sensing events follow the same probability distribution, as the selection of channels to sense is randomly performed by each sensing node, independently of any central authority and the choices of other nodes [11], [13]. For this process, the onset of activity of primary user between two sensing points is a random point in the sensing cycle.

If we denote the duration of the sensing period on channel σ as R and the moment of onset of primary user activity, relative to the previous sensing point, as ξ_R, then $\xi_R = R_-$ is the elapsed sensing time and $R - \xi_R = R_+$ is the residual sensing time. Since sensing periods are synchronized to piconet activity, they are multiples of the basic time slot used for MAC design. Therefore the probability distribution of sensing time is discrete, contrary to the distribution of activity times of primary users which are continuous and independent of piconet activities.

In [13], probability distribution of the residual sensing time with respect to the start of idle period was calculated in form of Probability Generating Function (PGF) to be $R_+(z) = \sum_{i=0}^{\infty} R_i z^i$, where values of mass probabilities R_i depend on the number of nodes in the piconet, traffic load, and scheduling parameter.

Finally, the process that counts superframes (on any channel) is also a renewal process, although a trivial one. In this case, the onset of activity of primary user on channel σ is a random point in the superframe currently ongoing on another channel μ. If we denote duration of superframe as $C = s_f$ and the onset of primary user activity relative to start of the superframe occurs at ξ_C, then $\xi_C = C_-$ is the elapsed superframe time and $C - \xi_C = C_+$ is the residual superframe time. Probability density function of the residual superframe time has the form $c = 1/s_f$ which can be obtained if expression (2) is applied to constant variable s_f; this holds for both discrete and continuous versions of the superframe residual time.

The piconet will not access a channel immediately after it becomes idle. Instead, a channel can be selected for the next hop only after (1) being sensed as idle, and (2) after that sensing outcome is recorded in the coordinator's channel map. Channel state change may be detected in the superframe where the change has occurred – if some of the sensing nodes sense that channel immediately after the end of primary user activity – or in one of subsequent superframes. Since the selection of channels to sense is randomly performed by each sensing node, independently of any central authority and the selection of other nodes [13], the time between the moment when the channel becomes idle (i.e., the primary user transmission ends) and the moment when the CPAN can access it is a random variable, and change of channel state is a random point in the sensing period.

Therefore, the time between a change of channel state and next sensing of that same channel is, in fact, the residual sensing time [5]. More specifically, a change of state of a given channel occurs at a random point of a piconet superframe, so the time period between that point and the moment of reporting of sensing results has the probability distribution of residual superframe time [5]. If channel state changes during the reporting subframe, sensing of the new channel state will be completed in the following superframe(s). Taking into account the sensing process, channel dynamics, and CPAN hopping, we can say that a channel state transition will be detected in ongoing superframe only if the residual sensing time is shorter than the residual superframe time; it will be detected in the immediately following superframe if the residual sensing time is longer than the residual superframe time but shorter than the sum of residual superframe time and superframe length; and similarly for second, third, … superframes after the transition.

For simplicity, however, we calculate only the probabilities that an active-to-idle channel transition is detected in the ongoing superframe and two following superframes: $Ps_0 = \sum_{k=1}^{s_f} c \sum_{i=0}^{k} R_i$, $Ps_1 = \sum_{k=0}^{s_f} c \sum_{i=k}^{k+s_f} R_i$, and $Ps_2 = \sum_{k=0}^{s_f} c \sum_{i=k+s_f}^{k+2s_f} R_i$, respectively, and ignore the cases where detection occurs in later superframes, as the corresponding probabilities are very low, typically below 0.01 for network configurations considered in this work.

Then, the probability that access to an idle channel is not possible and the average period during which that access is not possible, can be calculated as

$$\begin{aligned} P\theta_0 &= \sum_{i=0}^{2} Ps_i \int_{x=0}^{s_f} c \int_{y=0}^{x+i\cdot s_f} a(y)dydx \\ \overline{Noa} &= Ps_0 c \int_{x=0}^{s_f} xdx + Ps_1 \left(s_f + c \int_{x=0}^{s_f} xdx \right) \\ &\quad + Ps_2 \left(2s_f + c \int_{x=0}^{s_f} xdx \right) \end{aligned} \tag{3}$$

Once the channel is recorded as idle in the coordinator's channel map, the CPAN can access that channel in the next superframe. As superframe duration is fixed at s_f, access can occur at any multiple of s_f slots (and, in fact, more than once) until the channel becomes busy again. Since sensing events are synchronized to the time channel availability is detected, we need to calculate mass probabilities $P\theta_k$ of access by the piconet in k-th superframe period ($k = 1, 2, \ldots$) after the channel is labeled as available. As channel availability is detected at a random time with respect to beginning of idle channel period, $P\theta_k$ may be obtained by integrating probability density of idle channel elapsed time over superframe durations:

$$\begin{aligned} P\theta_1 &= \frac{Ps_0 \int_{x=0}^{s_f} c \int_{y=x}^{x+s_f} a(y)dydx}{1-\theta_0} \\ P\theta_2 &= \frac{(Ps_0 + Ps_1) \int_{x=0}^{s_f} c \int_{y=x+s_f}^{x+2s_f} a(y)dydx}{1-\theta_0} \\ P\theta_k &= \frac{\int_{x=0}^{s_f} c \int_{y=x+(k-1)s_f}^{x+k\cdot s_f} a(y)dydx}{1-\theta_0}, \qquad k > 2 \end{aligned} \tag{4}$$

Probabilities θ_k need to be normalized to the probability $1-\theta_0$ that the idle channel is available for access.

The coordinator's channel map is not perfectly accurate due to the insufficient number of sensing nodes and discrete nature of the sensing process, and the corresponding probabilities have been derived in our earlier work [11]. Let a_1 denote the probability that the channel map considers a channel where primary activity has ceased to be busy and therefore unusable, and let b_1 denote the probability that a busy channel is still considered to be idle in the channel map [11]. Therefore, the probability that the CPAN will access a given channel is $pc = (1-a_1)/(\overline{N_i}(1+b_1))$. Note that, in general, $a_1 \neq b_1$, due to different durations of active and idle channel periods.

Then, the probability that the CPAN will access a target channel at least once during its idle time (and not collide with onset of primary activity) can be calculated as

$$P_{acc} = \sum_{i=0}^{2} Ps_i \sum_{k=1}^{L} pc(1-pc)^{k-1} \int_{x=0}^{s_f} c dx \int_{x+ks_f}^{\infty} t_i(y)dy \quad (5)$$

Note that value a_1 is subtracted since idle channels with obsolete information are considered busy, and therefore will not be chosen for CPAN use.

In an analogous fashion, the probability that the CPAN will not attempt to access an idle channel is

$$\begin{aligned} P_{nvis} = {} & Ps_0 \sum_{k=1}^{L} (1-pc)^k \int_{x=0}^{s_f} c dx \int_{x+(k-1)s_f}^{x+ks_f} t_i(y)dy \\ & + Ps_1 \sum_{k=1}^{L} (1-pc)^k \int_{x=0}^{s_f} c(x)dx \int_{(k+1)s_f-x}^{(k+2)s_f-x} t_i(y)dy \quad (6) \\ & + Ps_2 \sum_{k=1}^{L} (1-pc)^k \int_{x=0}^{s_f} c(x)dx \int_{(k+2)s_f-x}^{(k+3)s_f-x} t_i(y)dy + a_1 \end{aligned}$$

We also need the probability that the CPAN will collide with the primary user on a given channel. The two types of collisions outlined above have different probability of occurring: b_1 is the probability of type 1 collision (i.e., that the piconet hops to a busy channel), while the probability of type 2 collision (i.e., that the channel will become active during superframe time) can be calculated as the probability that residual idle channel time is shorter than superframe duration:

$$P_c = \int_{x=0}^{\infty} (A(x+s_f) - A(x))a(x)dx \quad (7)$$

We note that $P_c + P_{acc} + P_{nvis} = 1$. Then, the total collision probability can be calculated as

$$P_{Col} = P_c + b_1 \quad (8)$$

Let the trailer contain a total of l next-hop channels, the first of them used as the next-hop channel in normal operation, and the remaining $l-1$ ones used as backup channels in case of collision. Note that, during normal operation, this list is updated in each trailer, as the channel conditions change. Upon a collision the recovery will be attempted at up to $l-1$ backup channels; only if all of these fail will the piconet revert to the rendezvous procedure. However, no sensing is conducted after a collision, so the information about backup channels becomes increasingly obsolete. As the result, the probability of hopping to another channel and experiencing another collision there increases in each subsequent recovery attempt, although this may be alleviated to some extent by using smaller superframe size $s_{fm} < s_f$. To model this effect, we need to modify expressions (7) and (8) in order to obtain probability that residual idle channel time is larger than i superframe times:

$$P_{c,i} = \int_{x=0}^{\infty} (A(x+is_{fm}) - A(x))a(x)dx \quad (9)$$

$$P_{Col,i} = P_{c,i} + b_1 \quad (10)$$

Then, the LST for the duration of recovery procedure, conditioned on collision on the current superframe, becomes

$$T^*_{rec}(s) = \sum_{j=1}^{l-1} \left(\prod_{n=2}^{j} P_{Col,n} \right) (1 - P_{Col,j+1}) e^{-sjs_{fm}} \quad (11)$$

Its mean value and standard deviation are obtained as

$$\overline{T_{rec}} = -\frac{d}{ds} T^*_{rec}(s)\big|_{s=0} \quad (12)$$

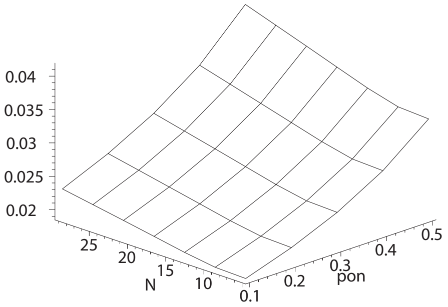
$$\sigma(Trec) = \sqrt{\frac{d^2}{ds^2} T^*_{rec}(s)\Big|_{s=0} - \overline{T_{rec}}^2} \quad (13)$$

IV. PERFORMANCE OF THE RECOVERY PROTOCOL

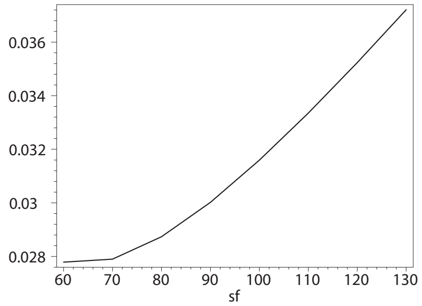
We have solved the recovery model, integrated with sensing and transmission models taken from [15], [13], using Maple 13 software package by Maplesoft, Inc. [10]. We have set the time unit to a single basic slot, superframe duration was fixed to $s_f = 100$ units, with the administrative portion of the superframe in normal operation (including reporting, reservation and join requests, beacon, trailer, and guard intervals) set to $\Delta = 20$ units. We have assumed that the piconet has $M = 16$ nodes, with each node having a buffer for a total of $K = 10$ packets. Packet arrival process was set to Poisson with arrival rate of $\lambda = 0.002$ packets per slot per node, while packet duration was uniformly distributed between 8 and 12 time units with an average value of $k_d = 10$. Duration of the acknowledgment packet was set to one time unit. Packet destinations were uniformly distributed over all piconet nodes. Maximum number of packets from a single node that can be serviced in one superframe is $\mu = 3$. Transmission tax was set to $k_p = 4$ superframes per one transmission, regardless of the number of packets sent. Sensing of one channel, including the time needed to switch to the channel, was assumed to take $d_s = 5$ slots.

The probability of collision with the primary user activity is shown in Fig. 2, with primary user cycle time fixed at $T_{cyc=3000}$ unit slots. When the superframe duration is fixed at $s_f = 100$ and the number of channels and primary user activity factor are made variable, as in Fig. 2(a), we note that the probability of collisions increases with primary user activity factor, which makes idle periods become shorter. It also increases with the number of channels on account of reduced accuracy of the channel map. Namely, since the number of nodes, their packet arrival rate, and the penalty coefficient all have fixed values, the ‘amount’ of sensing in the piconet is constant. When there are more channels, this translates into reduced sensing frequency per channel and, consequently, increases sensing error.

On the other hand, when the number of channels and primary user cycle time are fixed, collision probability strongly depends on the superframe duration – longer superframes increase the chance of collision. However, collision probability flattens when the superframe size s_f drops below 70 unit slots. This justifies the decision to conduct the recovery procedure using shorter superframe duration; in the experiments that



(a) Collision probability vs. number of primary channels N and primary user activity factor p_{on}, superframe size fixed at $s_f = 100$.



(b) Collision probability vs. superframe duration s_f, $N = 30$ primary channels with duty cycle of $p_{on} = 0.33$.

Fig. 2. Collision probability under mean primary user cycle time of $\overline{T_{cyc}} = 3000$ unit slots.]

follow, we have used $s_f = 100$ unit slots during normal operation and $s_{fm} = 50$ unit slot during recovery.

First, we have varied the number of backup channels, from $l = 3$ to 7, while keeping the mean primary user cycle time fixed at $t_{cyc} = 3000$ unit slots. The corresponding recovery times are shown in Fig. 3, with the diagrams for mean value and coefficient of variation (obtained as the ratio of standard deviation and mean value) shown on the left- and right-hand side, respectively. As can be seen, larger number of backup channels leads to shorter mean recovery times; however, the decrease gradually diminishes, and the difference between $l = 5$ and 7 is quite small. At the same time, the coefficient of variation decreases substantially, from the range 1 to nearly 1.8 in Fig. 3(d), to the range 0.14 to 0.22, in Fig. 3(f). This difference is due to the probabilistic character of the recovery process: at low values of l, recovery may be accomplished quickly but it may also fail, if all $l-1$ backup channels happen to be busy. When l increases, it is more likely that the recovery procedure will ultimately find an idle channel, from which the piconet can continue its normal operation. Still, the important conclusion is that even a small number of backup channels – say, three to five – suffices for reliable recovery.

We have also varied the mean primary user cycle time from $T_{cyc} = 1500$ to 6000 unit slots; the results are shown in Fig. 4 for $l = 3$ backup channels. As can be seen, shorter cycle times lead to higher recovery times. This effect is due to the increased probability of collision on a backup channel caused by shorter idle periods, even though (as explained above) the sensing accuracy is actually higher when the number of channels is smaller, for fixed number of piconet nodes, their arrival rate, and penalty coefficient.

Finally, we note that the recovery time values may be dependent on the actual probability distribution of idle and busy times on the channel. In this work we have assumed that primary user activity follows a memoryless probability distribution; the investigation of the behavior under other probability distributions remains as a promising direction for future research.

V. CONCLUSION

In this paper we have described a simple recovery mechanism, integrated with the transmission tax-based MAC protocol, for fast recovery of channel hopping cognitive personal area networks in case of collisions caused by primary user activity. We have shown that the recovery time is mostly dependent on the primary user activity factor, and to a somewhat lesser extent to the primary user cycle time, the number of channels, and the duration of the superframe. The good news is that a small number of backup channels is sufficient for speedy recovery, typically within one or two superframes after a collision.

Our future work will focus on practical implementations and tuning of the recovery mechanism, and on the integration of recovery with rendezvous mechanisms used for piconet formation and maintenance. We also plan to work on estimation of primary user activity patterns, if the primary user activity does not follow a memoryless probability distribution.

REFERENCES

[1] I. F. Akyildiz, W.-Y. Lee, and K. Chowdhury. CRAHNs: Cognitive radio ad hoc networks. *Ad Hoc Networks*, 7(5):810–836, 2009.

[2] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty. NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey. *Computer Networks*, 50:2127–2159, 2006.

[3] C. J. L. Arachchige, S. Venkatesan, and N. Mittal. An asynchronous neighbor discovery algorithm for cognitive radio networks. In *3rd IEEE Int'l Symp. on New Frontiers in Dynamic Spectrum Access Networks DySPAN 2008*, Chicago, IL, Oct. 2008.

[4] C. Cordeiro, K. Challapali, D. Birru, and N. Sai Shankar. IEEE 802.22: the first worldwide wireless standard based on cognitive radios. In *IEEE Int'l Symp. on New Frontiers in Dynamic Spectrum Access Networks DySPAN 2005*, pages 328–337, Baltimore, MD, Nov. 2005.

[5] D. P. Heyman and M. J. Sobel. *Stochastic Models in Operations Research, Volume I: Stochastic Processes and Operating Characteristics*. McGraw-Hill, New York, 1982.

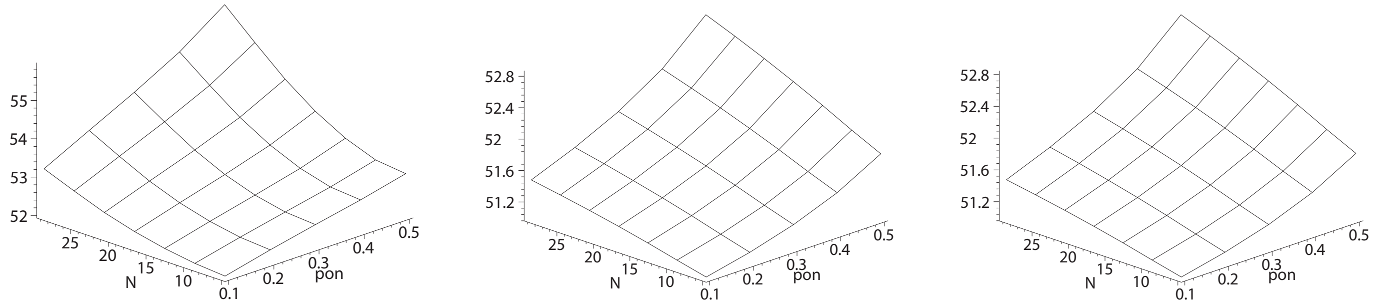
[6] B. Horine and D. Turgut. Link rendezvous protocol for cognitive radio networks. In *2nd IEEE Int'l Symp. on New Frontiers in Dynamic Spectrum Access Networks DySPAN 2007*, pages 444–447, Dublin, Ireland, Apr. 2007.

[7] P. K. Lee. Joint frequency hopping and adaptive spectrum exploitation. In *IEEE Military Communications Conference MILCOM2001*, volume 1, pages 566–570, Washington, DC, Oct. 2001.

[8] B. F. Lo, I. F. Akyildiz, and A. M. Al-Dhelaan. Efficient recovery control channel design in cognitive radio ad hoc networks. *IEEE Transactions on Vehicular Technology*, 59(9):4513–4526, 2010.

[9] L. Ma, X. Han, and C.-C. Shen. Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks. In *IEEE Int'l Symp. on New Frontiers in Dynamic Spectrum Access Networks DySPAN 2005*, pages 203–213, Baltimore, MD, Nov. 2005.

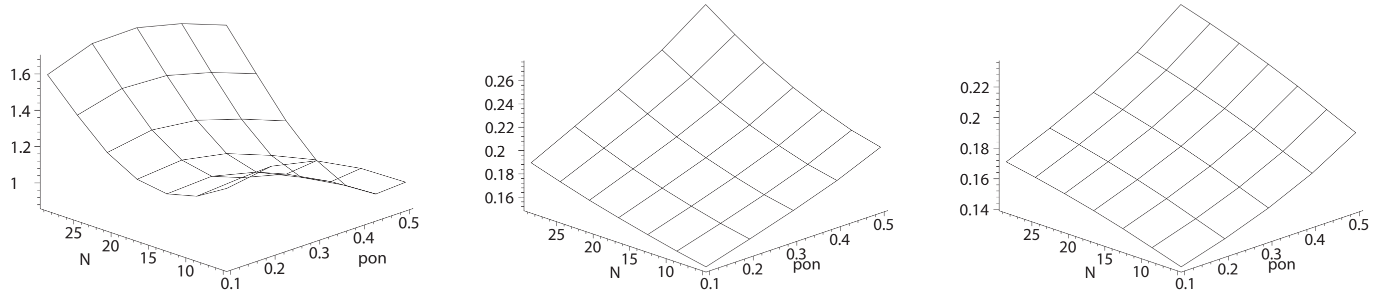
[10] Maplesoft, Inc. *Maple 13*. Waterloo, ON, Canada, 2009.



(a) Mean recovery time with $l = 3$ backup channels.

(b) Mean recovery time with $l = 5$ backup channels.

(c) Mean recovery time with $l = 7$ backup channels.

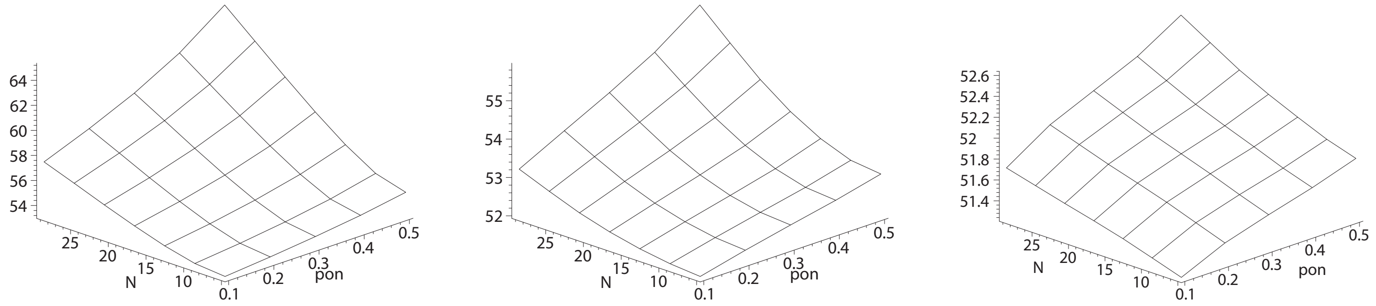


(d) Coefficient of variation of recovery time with $l = 3$ backup channels.

(e) Coefficient of variation of recovery time with $l = 5$ backup channels.

(f) Coefficient of variation of recovery time with $l = 7$ backup channels.

Fig. 3. Recovery time as function of the number of backup channels.



(a) Mean recovery time, primary user cycle time $T_{cyc} = 1500$.

(b) Mean recovery time, primary user cycle time $T_{cyc} = 3000$.

(c) Mean recovery time, primary user cycle time $T_{cyc} = 6000$.

Fig. 4. Recovery time with $l = 3$ backup channels.

[11] J. Mišić and V. B. Mišić. Performance of cooperative sensing at the MAC level: Error minimization through differential sensing. *IEEE Transactions on Vehicular Technology*, 58(5):2457–2470, June 2009.

[12] J. Mišić and V. B. Mišić. Simple and efficient MAC for cognitive wireless personal area networks. In *Proc. Global Telecommunications Conference GLOBECOM'09*, Honolulu, HI, Nov. 2009.

[13] J. Mišić. Cooperative sensing at the MAC level in simple cognitive personal area networks. *IEEE J. on Selected Areas in Communications – Wireless Series*, 30(9):1711–1718, 2012.

[14] J. Mišić, H. Khojasteh, N. Khan, and V. B. Mišić. Towards an efficient rendezvous protocol for a cognitive PAN. In *IEEE International Conference on Communications (ICC'2012)*, Ottawa, ON, June 2012.

[15] J. Mišić and V. B. Mišić. Trading delay for fairness in MAC design for cognitive personal area networks. In *Proc. GlobeCom 2009*, Honolulu, HI, Dec. 2009.

[16] V. B. Mišić and J. Mišić. Cognitive MAC protocol with transmission tax: Dynamically adjusting sensing and data performance. In *Proc. Global Telecommunications Conference GLOBECOM'10*, Miami, FL, Dec. 2010.

[17] W. Yin, Z. Wen, S. Li, J. Meng, and Z. Han. Dynamic compressive spectrum sensing for cognitive radio networks. In *45th Ann. Conf. Information Sciences and Systems (CISS 2011)*, pages 1–6, Baltimore, MD, 2011.