Properties of Blind Rendezvous in Channel Hopping Cognitive Piconets

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Abstract—Rendezvous refers to the ability of cognitive nodes to find each other and form a network, or to find an already operating cognitive network and join it. It is a challenging problem, in particular in channel-hopping cognitive networks. In this paper, we discuss the performance of the probabilistic blind rendezvous mechanism based on the transmission-tax-based MAC protocol with cooperative sensing at the MAC level. We investigate the performance of the algorithm, with particular focus on the difference in performance in an emergent vs. a fully operational channel hopping cognitive piconet.

I. INTRODUCTION

Channel hopping using a dynamically adaptive hopping sequence [13], similar to Bluetooth [11], [18], is a promising approach to avoid interference to and from licensed (primary) users in a cognitive network. Since this mode of operation resembles more traditional personal area networks, we refer to such networks as channel-hopping cognitive personal area networks, or CPANs in general, and to individual networks as piconets. One of the outstanding problems in CPAN development is the problem of rendezvous. Namely, to establish communication, a cognitive node must first attempt to meet another cognitive node (or an entire network) at the same RF channel and exchange synchronization data [10]. Channel hopping makes this problem particularly difficult because the individual hopping sequences of the nodes are not only different, but may change in time as well.

A number of approaches to the rendezvous problem have been proposed, with or without the aid of a dedicated infrastructure such as a central (base) station or a common control channel [7]. For obvious reasons, the latter approaches, collectively referred to as blind rendezvous [2], are preferable in practice. In this paper we investigate the performance of one such rendezvous mechanism [21], [22] developed in the context of the transmission-tax-based MAC protocol [23] which incorporates spectrum sensing [19]. This mechanism ensures that rendezvous is achieved in the presence of primary user activity, and it does not require that the clocks of different devices are synchronized. Moreover, rendezvous can be achieved during piconet formation as well as during normal operation of the piconet; we refer to those two scenarios as the emergent and fully operational piconet case, respectively.

The rest of the paper is organized as follows: Section II surveys related work and highlights the rendezvous problem in more detail. Section III describes the probabilistic rendezvous mechanism in the transmission-tax-based MAC protocol, while Section IV presents and compares rendezvous performance in an emergent and fully operational piconet case. Finally, Section V concludes the paper and highlights some future research.

II. RELATED WORK

In recent years a number of MAC protocols have been proposed for cognitive ad hoc and personal area networks [6]. Regarding the rendezvous problem, some solutions rely on the services of a central controller (e.g., [4]) or the availability of a dedicated common control channel [5], [17], [3], [7]. While both approaches promise good performance, i.e., short mean value and small (and provable) upper bound for time to rendezvous (TTR), their prerequisites – namely, a dedicated control channel or a central controller – are difficult to achieve in practice. Consequently, a blind rendezvous protocol is much better suited for truly distributed, autonomous cognitive networks [2].

Over time, two main approaches to blind rendezvous in cognitive networks have emerged. A large group of protocols rely on predefined deterministic channel hopping sequences [8], [9], [15], [16] (so it is questionable whether they should be considered to be truly blind). The necessary channel hopping sequences may be constructed in such a way that a finite upper bound for TTR is guaranteed, usually for two nodes finding each other, but sometimes even for multiple nodes finding others and establishing communication. However, most of these proposals suffer from the following shortcomings:

- First, they do not describe an actual rendezvous protocol, assuming instead that the rendezvous is accomplished when two nodes hop on a common available channel in the same time slot; obviously rendezvous can’t be made if both nodes transmit or receive at the same time.
- Some approaches rely on the nodes’ clocks and, by extension, their sequences, being synchronized – however, clock synchronization requires a central authority and, thus, it is not truly blind; furthermore, the clock phase shift (skew) may render the algorithm unusable.
- Most importantly, virtually all of sequence-based approaches simply ignore the presence of primary users and the impact of their activity – which is the basic tenet of cognitive communications. Categories of blind rendezvous protocols have emerged over time.
- In addition, most papers focus on the scenario in which nodes just find each other and establish communication, instead of the scenario in which a node finds and joins an operational piconet. This approach is similar to that one

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- In addition, most papers focus on the scenario in which nodes just find each other and establish communication, instead of the scenario in which a node finds and joins an operational piconet. This approach is similar to that one
adopted in Bluetooth [11], where the discovery procedure
(as rendezvous is called in Bluetooth) is mutually exclu-
sive with normal operation of the piconet. Such separation
of rendezvous and normal operation is impractical in
many scenarios such as emergency network operation,
disaster management, military communications, and the
like, where uninterrupted operation of the piconet is a
must, yet new nodes should be allowed to join as soon
as they appear in the vicinity.

We note that steps towards a piconet-oriented rendezvous
protocol have been made, e.g., the network setup protocol
described in [2], even this protocol depends on a central
controller (called Cognitive Base Station) and does not
entirely address the problem of avoiding interference
from primary users.

On account of these shortcomings, rendezvous protocols
in the other group appear to be more attractive in practice.
Typically they rely on spectrum sensing and probabilistic
channel selection, possibly aided by knowledge about primary
user activity patterns obtained through some kind of learning
[12], [10], [7], [22], [14]. Still, many of these protocols are not
well integrated with the MAC protocol and require separation
of rendezvous phase from normal operation. Recently, a MAC
protocol has been described [20], [23] that may be easily
extended to include a probabilistic rendezvous mechanism.
This extension is the focus of the present paper.

III. PROBABILISTIC RENDEZVOUS IN TRANSMISSION
TAX-BASED MAC PROTOCOL

In the transmission tax-based MAC protocol, nodes are
organized in piconets managed by a coordinator node, similar
to Bluetooth [11]; as in Bluetooth, any node with sufficient
computational capability may take up this role. Time is slotted
into unit slots and organized in superframes, each of which
takes place on a single channel; between two successive
superframes, all nodes in the CPAN hop to the next channel as
instructed by the coordinator. We assume that the superframe
contains $s_f$ unit slots, some of which are reserved for adminis-
trative purposes such as reporting of sensing results, join/leave
and bandwidth reservation requests, beacon and trailer frames.
There is also a guard time during which all nodes hop to the
next channel.

Each node can request time (i.e., bandwidth) for transmitting
a number of up to $\mu$ data packets. Upon successful trans-
mission, the sender node is obliged to perform sensing for
$k_p$ superframes. Sensing nodes independently and randomly
select which channels to sense during the data subframe of
a superframe, and report the results back to the coordinator
in the reporting subframe. The coordinator then 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.
Due to discrete character of sensing and the delay needed to
collect the sensing results, the information in the coordinator’s
channel map differs from the actual state [19]; the sensing
error may be controlled through judicious choice of $k_p$ [23].

Sensing duty may span several superframes when the trans-
mission tax coefficient is greater than one. We assume that
reporting is done in each of the $k_p$ superframes, which reduces
the sensing error and improves throughout by allowing the
sensing node to receive data when needed.

Many existing superframe-based MAC protocols require the
beacon frame to be sent at the beginning of the superframe;
however, the rendezvous protocol is better served by a trailing
beacon or trailer. Namely, a node that overhears any valid
frame in a superframe with a leading beacon will wait for the
reservation sub-frame (which would then be the last one in
the superframe) to send a join request. However, such a node
could not know which channel to hop to in order to hear
the next beacon, and thus would lose synchronization with the
CPAN. A simple remedy would be to make the coordinator
acknowledge a properly received join request packet with an
ACK packet indicating the channel to be used for the next
hop (and next superframe). However, should the join request
packet or the coordinator’s ACK packet get lost due to noise
and/or interference, the node would still have no idea where
to hop next and thus lose synchronization with the CPAN it
has discovered only a moment ago.

The trailer includes bandwidth allocation for previously
received transmission requests and the next-hop channel. It
also includes announcements about join/leave requests granted
by the coordinator, as explained in the next subsection.

We assume that all nodes are aware of the set of $N$ channels
to be used. Initially, a cognitive node may spend some time
trying to find if there is an operational CPAN in the vicinity;
if such a CPAN is not found, the node will immediately begin
to act as a coordinator, emitting beacon frames and hopping
through available channels in a pseudo-random manner, trying
to select idle channels (i.e., those without primary user activ-
ity) for its operation. Initially sensing will be performed by
the coordinator; as other cognitive nodes join the CPAN using
the rendezvous protocol, they will begin to exchange data
and thus gradually take over the sensing function. However,
basic functions of the CPAN (i.e., emitting beacon and trailer
frames, bandwidth allocation, and admission of new nodes)
will continue to be executed by the coordinator.

A newly arrived node that wants to find the CPAN (hereafter
referred to simply as the node) must also hop randomly
through the channels, as random hopping was shown to be
the most efficient approach to rendezvous [1]. The node may
hop to a channel which is busy, i.e., there is a primary user
active on that channel; it will stay there for only a short time
period, $T_{wb}$, which will be referred to as the busy timeout.
The node may also hop to an idle channel, where it will stay
for a longer time, hoping that the CPAN will eventually hop
in to the same channel. The maximum residence interval in
this case is referred to as the idle timeout, $T_{wi}$.

A new node that wants to find an operational CPAN may
hop onto a busy channel, in which case it stay there for
the duration of the busy timeout, $T_{wb}$. It may also hop to an idle
channel, where it stays up to $T_{wi}$, the idle timeout, unless it
makes the rendezvous or the channel becomes busy.
Once the node hops in to the channel, it will begin to wait for CPAN transmissions. Rendezvous succeeds in the following scenarios.

In the simplest one, the CPAN hops in to the same channel and begins a superframe. The node recognizes the presence of the CPAN, waits for the reservation subframe, and sends a request to join the CPAN; the coordinator grants the request and announces the presence of the new node in the trailer. If the node has heard a transmission from a CPAN, it may prolong its stay beyond the time $T_{wi}$ in order to send its join request and hear the admission decision in the trailer. In the ideal case, all of these occurs without interference from a primary user transmission.

The node may also hop to the channel on which the CPAN superframe has already started. Rendezvous may be achieved as long as the node can send in the join request in the reservation subframe.

Finally, rendezvous can be achieved even if the node hops to the channel just in time to hear the trailer. The node will thus be able to follow the CPAN to the next hop and send its join request in the next superframe.

However, rendezvous can also fail, on account of the following. First, the CPAN superframe might be completed on the channel visited by the node before the arrival of the node to the channel.

Second, the node sojourn on an idle channel may exceed the its idle timeout so that the node leaves before the arrival of the CPAN.

Finally, the node and the CPAN may visit an idle channel and attempt to make a rendezvous, but the communication between the two and, consequently, the rendezvous are effectively destroyed by the onset of primary source activity. (Note that the onset of primary source activity will also destroy the ongoing CPAN superframe.)

Let us now analyze the performance of the rendezvous protocol.

IV. PERFORMANCE RESULTS FOR PROBABILISTIC RENDEZVOUS

We have assumed that channel idle and busy times due to primary user activity are exponentially distributed with average values $T_i$ and $T_a$ respectively. Primary user activity factor $p_{on} = \frac{T_i}{T_i + T_a}$ was varied in the range 0.1 to 0.5, which corresponds to low- to medium primary user activity. (A duty cycle of 0.5 means that mean durations of active and idle periods are equal.) The mean cycle time of primary user transmissions was set to $T_{cyc} = T_i + T_a = 3000$ or 6000 basic slots. For convenience and to avoid any over-reliance on an actual technology, all time intervals are normalized to a single sensing slot (basic slot).

Regarding the duration of the superframe, we have considered two cases. In the first case, hereafter referred to as emergent piconet, superframe duration was $s_f = 50$ units, which fits the scenario in which the CPAN is in the process of build-up and there is no actual data exchange. In this scenario the piconet consists of just the coordinator which emits beacon
and trailer frames. Since there is no data traffic, the superframe
duration was set to $s_f = 50$ basic slots. A portion of that time,
lasting for $\Delta = 20$ units, was set aside for reservation and join
requests, beacon, trailer, and guard intervals. The coordinator
performs the sensing itself during the data transmission sub-
frame; sensing of one channel, including the time needed to
switch to the channel, was assumed to take $d_s = 5$ slots.

We have also set up an experiment where a node attempts
to find and join a CPAN piconet which fully operational. In
this case, the piconet has the superframe duration of $s_f =
100$ slots and $M = 16$ nodes, each having a buffer of size $K = 10$ 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 transmission, regardless of the
number of packets sent.

In both cases, the parameters of the rendezvous protocol
were set as follows: the busy timeout was fixed at $T_{wh} = 10$
unit slots, while the idle timeout was set to the product of the
number of primary channels and normalized timeout parameter
$nTOI$, i.e., $T_{wi} = nTOI \cdot N$.

The diagrams in Fig. 1 shows main performance descriptors
of the probabilistic algorithm in the emergent piconet scenario.
The diagrams in the top row present the mean TTR, while
those in the bottom row show the coefficient of variation of
TTR. As can be seen from the diagrams in the leftmost
column, mean TTR decreases with an increase in primary user
duty cycle. This is not unexpected since larger value of duty
cycle correspond to shorter idle time which, in turn, increases
the probability of overlap between CPAN and node residence
times conditioned on their meeting at an idle channel. At the
same time, mean TTR decreases when normalized timeout
$nTOI$ increases; the effect is more pronounced at larger
channel idle times. Coefficient of variation of rendezvous time
is in the range of 1 to 1.08 which indicates that the distribution
of rendezvous time is mildly hyperexponential.

On account of these results, we have chosen to use the
value of $nTOI = 140$ for the normalized idle timeout of the
probabilistic rendezvous algorithm in further experiments.

The other two sets of diagrams show the impact of primary
user cycle time under variable number of channels and primary
user duty cycle. At smaller cycle time $T_{cyc} = 3000$, TTR
has a minimum around 13 channels, while for $T_{cyc} = 6000$
rendezvous time monotonically decreases when the number of
channels increases. Minimal mean TTR is also accompanied
with sub-exponential values of the coefficient of variation of
TTR.

Basic performance descriptors for the operational piconet
scenario are shown in Fig. 2; as above, the diagrams in the top

Fig. 2. Rendezvous performance in the operational piconet scenario: top row, mean TTR; bottom row, coefficient of variation of TTR.
row present the mean Time-to-rendezvous (TTR), while those in the bottom row show the coefficient of variation of TTR. As can be seen, mean TTR and its coefficient of variation increase only slightly in comparison with the emerging piconet, mainly on account of longer superframe. Also, the coefficient of variation takes values in the range 1.02 to 1.12, which makes the distribution of TTR mildly hyperexponential.

When the number of channels increases, more channels become available for both the node and the CPAN to choose from; as the result, the mean TTR increases. Coefficient of variation of rendezvous time slightly increases with the number of channels and decreases when activity factor is growing, which is expected.

When the cycle time of primary source grows, mean TTR will also increase; however, coefficient of variation is slightly smaller when the channel cycle time increases since variation of unsuccessful waiting time is becoming smaller.

On the whole, performance of the probabilistic rendezvous is only slightly worse in the fully operational piconet scenario vs. that in the emergent piconet scenario. However, the operational piconet scenario allows the channel-hopping cognitive piconet to operate normally while still accepting new nodes, which would be an extremely desirable capability in many applications such as emergency/disaster response and others.

While the probabilistic rendezvous is a truly blind mechanism that can’t ensure a guaranteed mean TTR – unlike its sequence-based counterparts discussed in Section II – it is remarkably resilient to random primary user activity patterns. Moreover, the fact that its coefficient of variation is reasonably close to 1, thus indicating that its probability distribution is close to exponential, means that in practice such protocol would provide predictable performance in a wide range of primary user traffic.

V. CONCLUSION

In this paper we have proposed a probabilistic rendezvous algorithm in the context of a simple transmission tax-based MAC protocol for channel hopping cognitive personal area networks, and evaluated its performance in the context of an emergent piconet (which corresponds to the case when two cognitive nodes look for each other in order to establish communication) and an operational piconet which a newly arrived cognitive node wants to find and join. Mean TTR is shown to depend mostly on the number of channels and primary user activity factor, and to a somewhat lesser extent to the primary user cycle time.

Our future work will focus on practical implementations and tuning of these algorithms, including suitable recovery algorithms that will allow a transmission-tax based CPAN piconet to resume normal operation upon collision with primary user transmission. We also plan to work on estimation of primary user activity patterns, esp. in cases where primary user activity does not follow a memoryless probability distribution.

REFERENCES


