A BANDWIDTH SHARING APPROACH TO IMPROVE LICENSED SPECTRUM UTILIZATION

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Abstract - The spectrum of deployed wireless cellular communication systems is found to be under-utilized, even though licensed spectrum is at a premium. To efficiently utilize the bandwidth left unused in a cellular system, which we denote as the primary system (PRI), we design a system with an ad hoc overlay network, which we denote as the secondary system (SEC). The basic design principle is that the SEC operates in a non-intrusive manner and does not interact with the PRI. We develop the AS-MAC, an Ad hoc SEC Medium Access Control protocol to enable the interoperation of the PRI-SEC system. We address a number of technical challenges pertinent to this networking environment, and evaluate AS-MAC. Our performance evaluation results show that, in a single-hop ASN, the AS-MAC transparently utilizes 75% of the bandwidth left unused by the PRI, while, in multi-hop ASNs, due to spatial reuse, the AS-MAC can utilize up to 180% of the idle PRI resources.

I. INTRODUCTION

There is a strong belief that the spectrum both in the public as well as private sector in the United States is getting scarce. Recent measurements for cellular systems in major metropolitan areas ([1], [2]) suggest that spectrum utilization in several frequency bands is very low for extended periods of time. This means that the primary cause of spectrum scarcity is its inefficient utilization, rather than its unavailability. It also suggests that adoption of efficient modulation and coding techniques, which can clearly improve spectrum utilization, cannot alone address the inefficiency.

A promising approach, known as spectrum sharing or pooling [3], is to enable two systems accessing the same spectrum. The owner of the spectrum, which we denote as the *primary system* (*PRI*), can allow a *secondary system* (*SEC*) to operate in the same spectrum, under the assumption that *SEC* utilizes only the portion of the spectrum left unused by the *PRI*. One example of such a scenario is that of a cellular provider leasing its unused spectrum to a *SEC* when cellular traffic is expected to be significantly lower, e.g., between 9PM and 7AM. The *SEC* could be, for example, a mesh network providing peer-to-peer communication, or wireless Internet access.

In this paper, we consider the design of a *SEC* system overlaid on a *PRI* system, which, we assume is a *TDMA/FDMA* based *GSM* cellular network [14] with or without the use of frequency hopping. The *SEC* is a multi-hop ad hoc network, which we denote as the *Ad hoc Secondary Network* (*ASN*). The fundamental constraints for the *ASN* are (*i*) it operates only over the resources (i.e., bandwidth) left unutilized by the *PRI GSM*, (*ii*) its operation causes no performance degradation of the *PRI*, and *(iii)* there is no exchange of signaling information between the *PRI* and the *ASN*.

To enable such an approach, we propose here our *Ad hoc SEC Medium Access Control* (*AS-MAC*) protocol, a Multichannel *MAC* (*MMAC*) protocol responsible for the following basic tasks. First, *AS-MAC* detects the frequency bands utilized by the entities of the *PRI*, i.e., base station (*BS*) and the mobile stations (*MS*s). Then, *AS-MAC* creates and maintains a picture of the (portion of) *PRI* resources that remain unutilized. Finally, with this information at hand, *AS-MAC* provides a flexible facility for the *ASN* nodes (*AN*s) to access those resources for their communication, while satisfying the above-mentioned constraints (*i*)-(*iii*).

The contributions of this paper are, first, the identification of technical challenges in the development of such a *PRI-SEC* system, with the availability of *PRI* unutilized resources changing dynamically over time. Then, we develop a practical solution based on the *AS-MAC* protocol. Our evaluation of the protocol indicates that *AS-MAC* enables a single-hop *ASN* to efficiently utilize up to *75%* of the otherwise unused bandwidth of the *GSM PRI*, and multihop *ASN*s to utilize, due to spatial reuse up to *180%* of the available resources.

In the rest of the paper, we first provide an architectural view of the proposed system, identify the technical challenges therein, and discuss the basic ideas of our approach to address those challenges. The *AS-MAC* protocol is defined next, followed by implementation considerations. The protocol performance evaluation is presented, before we discuss additional aspects and future work. Finally, we survey related literature and conclude.

II. SYSTEM ARCHITECTURE AND OVERVIEW

An example of the physical architecture of the *PRI-SEC* system is illustrated in Figure 1: within the *GSM* system, *MS*s communicate with the *BS*, while *AN*s form a multi-hop, peer-to-peer topology within a *GSM* cell.[1] Each *AN* needs to first determine the communication structure of the *PRI*, as well as identify the available resources, which are the time-slots within each of the cell's frequency bands. Then, *AN*s utilize this available bandwidth to communicate, without interfering with the operation of the *PRI*.

Within a *GSM* cell, a set, *C*, of channel pairs, that is, frequency bands is allocated for use by the *BS* and *MS*s, out of $C_{total}=124$ available *GSM* bands [14]. For each voice call, one

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[1] The *ASN* can operate across multiple cells, as we discuss in Section VI, however, in this paper we evaluate *AS-MAC* within a *PRI* cell.

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channel is used for *BS* to *MS* (*downlink*) and one channel for *MS* to *BS* (*uplink*) communication. Each up- or down-link is divided into frames with T_S time slots per frame. The time slots are mapped onto logical control and traffic channels. Voice or data communication takes place on the traffic channels, while Signaling information is transmitted on the control channels. The Frequency Correction Channel (*FCCH*) and Synchronization Channel (*SCH*) enable the *MS*s to achieve time synchronization with the *BS*. The physical frequency that carries *FCCH* is denoted as the *beacon* frequency (or channel). The Broadcast Control Channel (*BCCH*) provides the Location Area Identity (*LAI*), the Cell Identity (*CI*), and the Cell Channel Description (*CCD*). The combination of *LAI* and *CI*, termed the *Cell Global Identity* (*CGI*), uniquely identifies a cell, while the *CCD* provides the list of cell frequencies, *C*. The common signaling channels are not encrypted, so that not only all *MS* but also all *AN*s within the cell radius can readily receive the *BS* signaling.

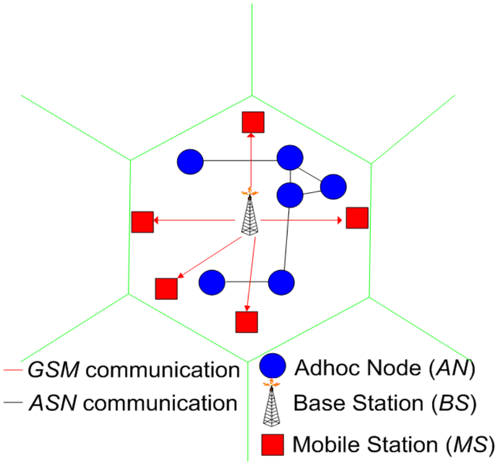

Figure 1. System diagram.

The first challenge is for each *AN* to determine the *PRI* communication structure. *AN*s first need to determine the slot boundaries (i.e. the beginning and end of each *PRI* time-slot); they can obtain this information by decoding the *FCCH* signaling from *BS*. Time synchronization can (or should) be performed periodically by *AN*s.[2] Then, *AN*s decode *SCH* and *BCCH*, with the latter providing the *CGI* and *CCD* of the current cell. Based on *CGI*, *ANs* determine if they are allowed to share the current cell *PRI* resources. *CCD* provides the information for *AN*s about frequencies that belong to the current cell.

Once the set of cell frequencies and the slots' timing are determined, the *ANs* need to create and maintain an up-to-date map of available time slots on the downlinks.[3] To do so, we assume that *ANs* are equipped with a *sensing module*, that is, hardware that provides the capability for wide-band spectrum sensing [15], [19], [20]. For our system, it suffices that the sensing module detects the presence of a signal (that is, energy level above a threshold) within each of the *C* bands. For a short period of time at the beginning of each slot, the sensing module detects if a *PRI* transmission takes place. If no transmission is sensed, it is definite that the *PRI GSM* will not utilize the current slot. Thus, if the sensed idle slot is utilized by the *ASN*, there will be no collision with or obstruction of the *PRI* traffic. We emphasize that without sensing on a per-slot basis, use of only left-unused resources (constraint (*i*)) for *ASN* transmissions cannot be ensured. This is so, because prediction of future *PRI* usage cannot, in principle, be flawless. For this paper, we assume that the sensing of *PRI* slots is perfect at all *AN*s. In a real system, the sensor will occasionally report a slot as occupied by *PRI* even when it is not (the sensor will be biased in a way that it gives false positives to avoid false negatives).

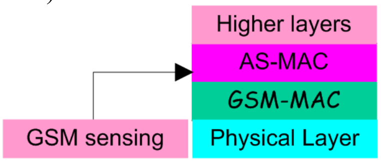

Figure 2. Protocol stack of the *ANs*.

The solution we are after seeks to enable any network protocol stack in the *ASN*. To achieve this goal, a protocol that acts as an intermediary between the *ASN* network layer and the *GSM* system is necessary. Essentially, such a protocol is a medium access control protocol from the point of view of the *ASN*. Yet, conceptually, *AS-MAC* operates on top of the *GSM MAC* protocol. We denote this protocol as *Ad hoc Secondary Medium Access Control* (*AS-MAC*). Figure 2 illustrates the *ASN* protocol stack.

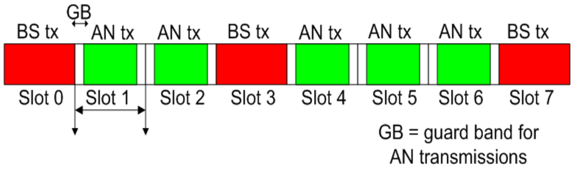

Figure 3. *GSM* Slot Utilization by *ASN* nodes.

The *AN*s have only one transceiver, while, in general, multiple *GSM* channels are available. *AS-MAC* provides for the selection of one among those channels. To do so, a handshake is necessary between the sending and receiving *AN*s: the sender provides candidate channels and the receiver selects a desirable channel. This exchange of information is performed across a commonly agreed, within the *ASN*, channel, which we denote as the *control channel* (*CC*). The actual data transmission takes place across the selected channel, among the remaining ones in *C*, which we denote as *data channels* (*DC*s).

Once the data channel is selected, *AS-MAC* has to actually transmit the data. In general, *ASN* packets can be larger than the number of bits that can be transmitted within an interval of *PRI* inactivity. This is clearly the case for a *GSM PRI* and the *GSM* slot. Thus, data need to be fragmented. The challenge here is that transmission must take place in available slots that are not consecutive. Since the occupancy (availability) of slots depends on the *PRI* traffic, time progress of the *ASN* protocol, in our case *AS-MAC*, must take place only when *PRI* slots are free. Otherwise, when there is *PRI* activity, *the state of the ASN protocol*

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[2] For example, *MS*s obtain timing information from the *BS* twice per second (when a call is in progress).

[3] We also note that available resources on the downlinks are utilized by the system described in this paper. Determining the boundaries of the slots in the uplinks would require cooperation from the *PRI* (i.e., the *BS*), which would violate constraint (*iii*).

must essentially freeze. Consider, for example, in Figure 3, a single time-slotted *GSM* downlink consisting of eight slots numbered *0* to *7*; slots *0*, *3*, and *7* used by the *PRI*, are shown in red, and available slots *1, 2, 4, 5*, and *6* are shown in green. If a message transmission is to occupy three slots, starting from slot 1, then, counting those slots must '*stop*' during slot 3, and resume with slot 4.

III. *AS-MAC* PROTOCOL OPERATION

A. *Sensing and channel usage*

ANs identify the *GSM* downlink frequencies using the *CCD* information broadcasted by the *BCCH* on the beacon frequency. Among the set, *C*, of *GSM* cell frequencies, *AN*s select the one with the highest index, other than the beacon frequency, as the *ASN* control channel (*CC*). The set C_d of remaining channels, are the data channels (*DCs*).

To detect if a slot is indeed unused by the *PRI*, *AN*s sense all the (downlink) channels in the cell during a period of time, τ, at the beginning of each slot of $T=577\mu s$. Sensing takes place after the *GSM* guard band ($15\mu s$). Currently, widely available transceivers such as the *802.11 DSSS PHY* layer mandate a maxium $\tau = 15\mu s$. We assume here that τ for *AN*s will be less than $15\ \mu s$. Through sensing, *ANs* create and update *pUsage*, statistics of the *PRI* slot usage history, with more recent samples having higher weights. This information is used to dynamically select the preferred data channel for each packet transmission. Nonetheless, such preference does not guarantee that the slot availability will remain as estimated, or does imply that any prediction of future usage is made. Instead, the sensing module is utilized at all slot boundaries to determine the actual slot availability.

Since the sensing module is utilized for τ seconds to sense *PRI* traffic, it is straightforward to also sense *ASN* transmissions. It suffices to activate the sensing module for a τ_{SEC} seconds after the primary signal sensing. We denote this as *secondary sensing*, performed both on the *ASN's* control and data channels. *AN*s maintain s*Usage*, a data structure indicating the data channels currently in use by other *AN*s.

After sending *RTS*, the sender freezes its state, in the sense that it waits until the end of the next free slot on the control channel to receive *CTS*. Clearly, unlike in traditional medium access control protocols, the sender cannot merely set a fixed timeout while expecting a *CTS*. This is so, because the *PRI* activity inescapably prevents any *ASN* transmissions, while the *AN*s do not know a priori the length of this activity.

B. *AS-MAC description*

With the resource availability information at hand, *AS-MAC* enables communication between any two neighboring *AN*s. Basically, *AS-MAC* provides the means for nodes to first agree upon a data channel, through a handshake that involves the exchange of three control messages, a *Request To Send* (*RTS*), a *Clear To Send* (*CTS*), and a *Reservation* (*RES*) message, transmitted in this order. Our experiments in section V.A show that the *RES* message may not be necessary, thanks to the sensing module. As a result, we identify and discuss two versions of *AS-MAC*, one which uses *RES* and we denote as $AS\text{-}MAC_1$, and one without *RES* denoted as $AS\text{-}MAC_2$. Since the latter is found more efficient, we discuss this variant below, referring to $AS\text{-}MAC_1$ and $AS\text{-}MAC_2$ interchangeably unless otherwise noted.

Figure 4 illustrates *AS-MAC*: an *AN* (the sender) waits for a free control slot and transmits (unicasts) *RTS* for an intended receiver after a period of time τ_{uRts} from the slot beginning, randomly selected from a uniform distribution $U(W_1, W_1+W_{\mathrm{uRts}})$, where $W_1 = 40\mu\mathrm{s}$ and $W_{\mathrm{uRts}} = 140\mu\mathrm{s}$. This randomness reduces collisions among *RTS*. The *RTS* contains a bit map of the channels in C_{d} that are preferred by the sender, and the number of *PRI* slots needed to transmit the packet, which we denote as *NAV*. The idea behind this *NAV* is similar to that in 802.11 except that now it is specified in terms of the number of free slots.

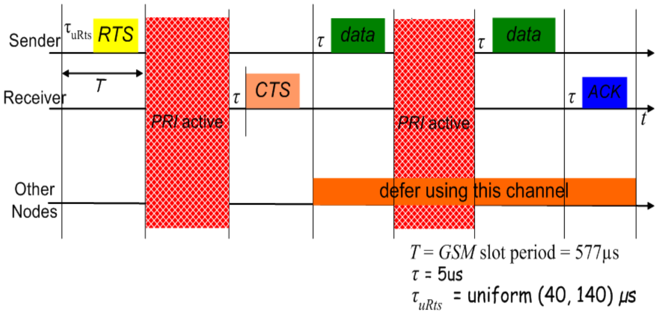


Figure 4. *AS-MAC* packet transfer

If *CTS* is not received, the sender increments a counter and *RTS* is retried in the next free slot, up to a maximum number of attempts. The *CTS* provides the receiver's and sender's *ID*, *NAV*, as well as the channel for communication. The selected channel is the one with the maximum number of free slots based in *PRI* traffic (measured over the last eight slots), among those at the intersection of the sets of channels preferred by the sender and receiver.

Essentially, a channel is 'preferred' if it is either sensed free, or known to be free based on prior receipt of *CTS* (or *RES*) packets from other nodes. An *RES* is sent by $AS\text{-}MAC_1$ upon receipt of *CTS*, containing the sender and receiver *IDs*, the *NAV*, and the chosen data channel, namely *c*. Thus, nodes receiving *CTS* (or *RES*) can unambiguously 'prohibit' themselves from using *c* until at least *NAV* free *PRI* slots elapse on *c*. We emphasize that the sender does not reserve a channel for a fixed duration of time, as is the case with *802.11* and *MMAC* protocols: in the *PRI-SEC* context, the *AN* cannot know the future slot usage of the primary, and thus cannot predict the transmission duration. Rather, *AS-MAC* counts the number of free slots required for transmitting the data packet and sets this value as the *NAV*. Third party *ANs* that receive the *CTS* and *RES* decrement the *NAV* counter only when a slot on *c* is *PRI*-free. Finally, note that *RES* and *CTS* also inform *ANs* to defer sending an *RTS* to a busy node, involved in the corresponding data transfer.

After the *RTS*/*CTS* (*RES*) handshake is completed, the sender fragments the packet and transmits the fragments, identified by an increasing sequence number, successively on free slots of the data channel. Figure 4 and Figure 5 illustrate that *AS-MAC* freezes its state, remaining idle in all slots utilized by the *PRI*. An *ACK* is expected from the sender upon completion of the transmission of all fragments, which is indicated by the sender's setting the *AckCount* field in fragment header. *AckCount* is a decreasing counter of the remaining fragments, and thus free slots, after which the receiver should send an *ACK*. Including *AckCount* in all fragments provides robustness to fragment loss: receipt of one packet fragment, not necessarily the first-transmitted one by the sender, suffices for the receiver to 'schedule' the *ACK* transmission, independently of how many of the packet fragments are received.

The *ACK* contains a list of *ID*s of the received fragments,[4] with the sender re-transmitting only the lost fragments. Partial retransmissions reduce network overhead, compared to full re-transmissions, an important aspect especially in a resource constrained environment. An example of an error recovery is illustrated in Figure 5: a packet consists of eight fragments, with *ID*s from *0* to *8*, with fragments *3* and *6* (shown in dotted lines) lost. The first *ACK* acknowledges all fragments except *3* and *6*, which are then retransmitted in the next cycle and the packet transfer is completed.

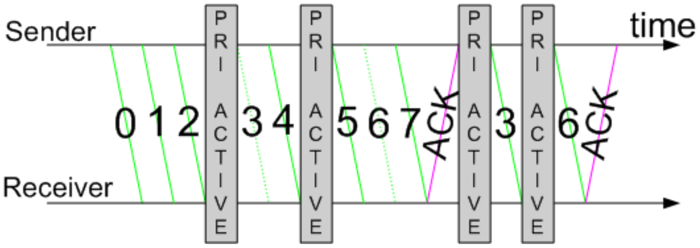
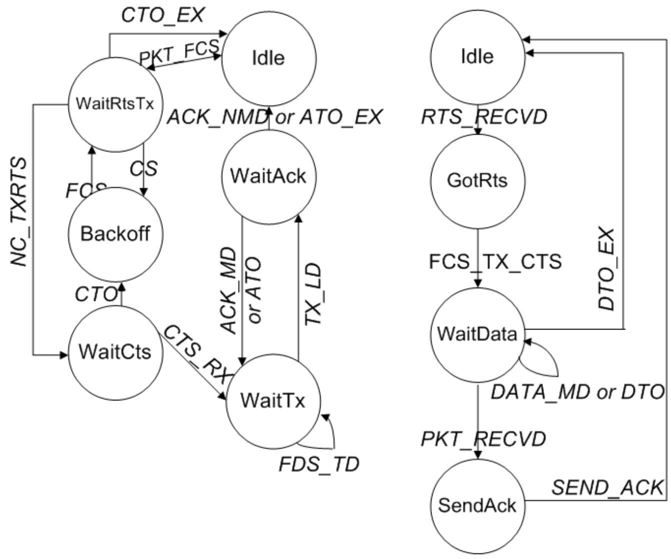


Figure 5. *AS-MAC* fragment error recovery process



(a) Sender (b) Receiver

Figure 6. *AS-MAC* state transition diagram

A maximum number of retransmissions is attempted by the sender (in the range of *4* to *7*), and the packet is aborted if not all fragments are received. Furthermore, in the event that no free slots are currently available on the chosen data channel, both the sender and receiver abort the transmission process (Recall that the sensing modules at both nodes provide this information).

Figure 6 shows the finite state diagrams of *AS-MAC* sender and receiver. Table 1 explains the conditions and actions for each transition. On receipt of an upper layer packet and the occurrence of a free slot on the control channel (*PKT_FCS*), the sender schedules an *RTS* transmission after a random time interval. If carrier is sensed (*CS*) it backs off and retries *RTS* on the next free control slot. If no carrier is sensed (*NC_TXRTS*), it sends *RTS* and waits for *CTS*. On a *CTS* timeout, it backs off and retries *RTS*. If *MAX_CTS_TIMEOUTS* are exceeded (*CTO_EX*), it goes back to the *IDLE* state. On receipt of *CTS* (*CTS_RX*), it goes into *waitTx* state and waits for a free data slot to transmit *DATA*. When it is done transmitting all pending fragments, it expects *ACK*, and goes into *waitForAck* state. Same thing happens when an *ACK* timeout takes place. When all fragments are transmitted and corresponding *ACK* is received (*ACK_NMD*), or when *ACK* timeouts are exceeded, the sender goes back to *IDLE* state. When a receiver receives *RTS*, it goes into *GotRts* state where it waits for a free control slot. Then it transmits *CTS* and goes into *waitData* state. On receipt of *DATA* or on a *DATA* timeout, and if more data are pending, it remains in the same state. When *MAX_DATA_TIMEOUTS* are exceeded (*DTO_EX*), it goes back to *IDLE* state. When the entire packet is received (*PKT_RECVD*), it sends an *ACK* and goes back to the *IDLE* state.

Condition/Action ID	*Description*
PKT_FCS	Packet available and free control slot / schedule *RTS* transmission
CTO	*Timeout / ++numCtsTimeouts*
CTS_RX	*CTS* received
CS	Carrier sensed
NC_TXRTS	No carrier / Tx *RTS*
FDS_TD	Free data slot and more than one *DATA*/ tx *DATA*
ACK _MD	*ACK* recvd and more *DATA*
ATO	*ACK* timeout / *++numAckTimeouts*
TX_LD	Free data slot and only one pending D*ATA* / tx *DATA*
ACK_NMD	*ACK* got and no more pending *DATA*
FCS	Free control slot
SEND_ACK	Free data slot / send *ACK*
ATO_EX	*MAX_ACK_TIMEOUTS* exceeded / drop packet
FCS_TX_CTS	Free control slot / send *CTS*
RTS_RECVD	Unicast *RTS* recvd
PKT_RECVD	Packet received completely / pass packet to higher layer
CTO_EX	*MAX_CTS_TIMEOUTS* exceeded / drop packet
DTO_EX	*MAX_DATA_TIMEOUTS* exceeded / drop packet
DATA _MD	*DATA* fragment got, more *DATA* pending
DTO	*DATA* timeout / *numDataTimeouts++*

Table 1. *AS-MAC* protocol conditions and actions

IV. IMPLEMENTATION CONSIDERATIONS

The *PRI-SEC* design objective to ensure that the *SEC* operation cause no *PRI* performance degradation (constraint (*ii*)) is paramount. However, sensing of idle periods (constraint (*i*)), explained in Sec. III.A, does not suffice to achieve this objective. This is so, because of the impact of propagation delays on the system operation. In particular, timing information *AN*s ob-

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[4] The *AS-MAC* maximum transmission unit (*MTU*) and the *ASN* physical layer determine the maximum size of the *ACK*.

tain from the *BS* signaling can be offset due to the signal propagation delay from the *BS* to the *AN*. Unlike *MS*s, which overcome such timing offset with the assistance of the *BS*, cannot correct their synchronization information, exactly because they cannot interact with the *PRI* (constraint (*iii*)). This results in an offset of the slot boundaries detected by *AN*s, with the offset proportional to the *AN-BS* distance. It is thus necessary to ensure that *ASN* and *GSM* (*BS* to *MS*) transmissions in adjacent slots do not overlap due to the synchronization offset. If not, and even though the *ASN* takes place in an indeed idle *PRI* slot, signal collisions and thus corruption of *PRI* packets would occur.

Figure 7 illustrates such a scenario, with $\tau_{BS\text{-}AN}$ and $\tau_{BS\text{-}MS}$ the propagation delays from the *BS* to an *AN* and *MS* respectively: (1) a *GSM* slot is free, (2) the *AN* detects the idle slot and transmits, (3) the *BS* transmits to the *MS* at the next slot, (4) the *MS* starts receiving *BS*'s transmission, (5) the last bit of the *AN* transmission reaches the *MS*, (6) the transmission from *AN* overlaps partially with *MS*'s reception, for a duration of $O=\tau_{BS\text{-}AN}-\tau_{BS\text{-}MS}+ d_{AN\text{-}MS}$, where $d_{AN\text{-}MS}$ is the propagation delay between *AN* and *MS*. It is important to note that when the offset of *AN* is less than that of *MS* (i.e., $\tau_{BS\text{-}AN} < \tau_{BS\text{-}MS}$), this term becomes negative and actually helps reduce the duration of overlap.[5]

The maximum overlap duration, *O*, assuming a maximum *GSM* cell size of *30Km*, is *200µs* (since the corresponding propagation delay is *100µs*) and occurs when: (*a*) *MS* is close to *BS* and *AN* is located at the cell boundary: $\tau_{BS\text{-}AN} - \tau_{BS\text{-}MS} = 100\mu s$ and $d_{AN\text{-}MS} = 100\mu s$ and (*b*): *AN* and *MS* are located at diametrically opposite sides of the cell: $\tau_{BS\text{-}AN} - \tau_{BS\text{-}MS} = 0\mu s$, and $d_{AN\text{-}MS} = 200\mu s$. It can be easily verified that for all other relative locations of *MS* and *AN* with respect to *BS*, the overlap durations are less than or equal to *200µs*. Thus, the maximum O depends on the propagation delay corresponding to the diameter of the cell. The impact of the overlap can be easily mitigated by adding a guard band of the same duration, *O*, at the end of *ASN* transmissions. But this would render more than *30%* of an idle *PRI* slot unusable.

Nevertheless, the *AN*'s signals are attenuated as they propagate, and this observation can lead to a more efficient solution to mitigate *ASN-PRI* interference. The basic idea is that rather than ensuring zero interference, we allow some overlap, but seek to ensure that interference level at the *MS*s above the *PRI* system threshold are negligible. Let the received power at a distance *r* from a transmitter is given by [13]:

$$P_r = P_t\left(\frac{\lambda}{4\Pi r}\right)^n g_t g_r \tag{1}$$

with P_r, P_t the received and transmitted powers, λ the carrier wavelength, g_t and g_r the antenna gains at the transmitter and receiver respectively, and n the path loss exponent.

One the one hand, as the distance of *AN* and *MS* increases, so does the received power of *AN*s signal at the *MS*, assuming that there is n overlap. On the other hand, as the guard band *x* increases, so does distance of *AN*s whose transmissions are guaranteed not to overlap with the reception at the *MS*. Thus, selecting such a guard band *x* essentially bounds the amount of additional interference imposed by all *AN*s. Table 2 shows representative values of the worst case *SINR* at the *MS*, with P_B the received *BS* signal strength at the *MS*, and *I* the worst case interference (due to overlap) from all *AN*s. It then suffices to select *x* so that the corresponding *AN* interference can be tolerated at *MS*s, given the expected interference from other sources, such as ambient noise and co-channel interference.

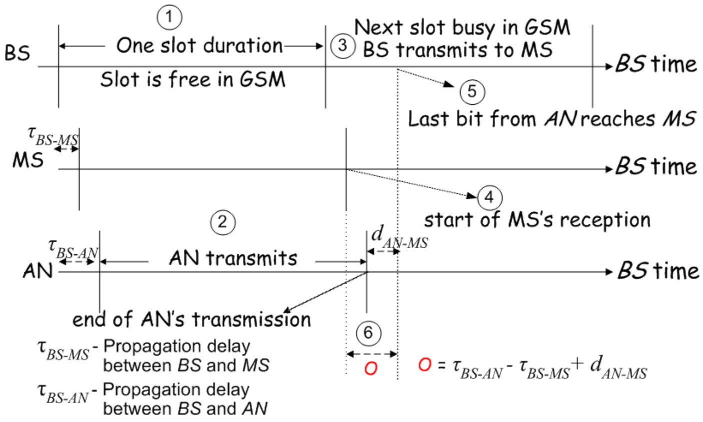

Figure 7. Interference between *AN* and *MS*.

Guard Band, *x* (*µs*)	*P_B/I* (*dB*)
3.33	*0*
6.66	*9*
10	*14.3*
13.32	*18*
16.65	*20.9*
20	*23.3*
23.33	*25.3*
26.66	*27*
30	*28.6*
33.33	*30*
36.66	*31.24*

Table 2. Variation of *AN* to *MS* interference Vs the allowed time margin for *AN* transmissions.

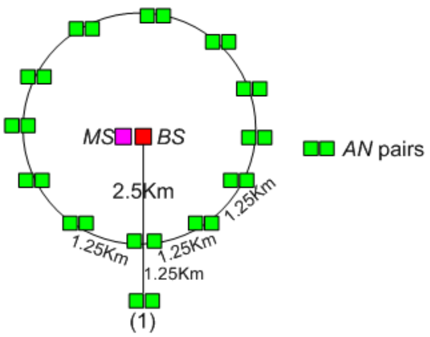

Figure 8. *AN* locations causing maximum interference to *MS*.

To illustrate the calculation of worst case *I*, consider Figure 8 for *x=16.65µs*, which implies that *AN*s located less than *2.5km* from *MS* will not interfere with reception at the *MS*. The locus of *AN* locations whose transmissions barely overlap with *MS*'s reception is a circle with the center at the *MS* and radius *2.5km*.

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[5] When *BS*, *AN*, and *MS* are collinear in that order it is possible that *O* can be zero, if $\tau_{BS\text{-}MS} - \tau_{BS\text{-}AN} = d_{AN\text{-}MS}$.

However, there are at most *12* possible *AN* pairs on this circle separated by the carrier sensing range of *ASN* (assumed, e.g., *2.5* times the transmission range, *2.5*500m=1.25km*). Then, *I* would increase, in the worst case, interference at the *MS* by *10.8dB*. The solution to thwart such an effect, even the worst case, is to increase *x* to *36.66μs*, which gives additional *11dB* robustness to interference.[6]

V. PERFORMANCE EVALUATION

We evaluate our system, studying the improvement in spectrum utilization due to the *ASN*, as well the performance of *AS-MAC.* We develop models of the *PRI-SEC* system and *AS-MAC* in *Qualnet* [17], and evaluate the performance of the *ASN* within a single cell of the *PRI GSM* system. We experiment with three *ASN* topologies, in all cases fully residing within the GSM cell, (*i*) a fully connected network of *20 AN*s, (*ii*) a *10*-by-*10* grid topology, and (*iii*) a random topology with *100 AN*s having uniformly random locations within a *1000m* by *1000m* square area. In the experiments presented here, *AN*s are static (no mobility), as our objective to evaluate the data link performance for the *ASN*. The *AN*s nominal transmission and sensing ranges are *250m* and *625m* respectively, with a *10dB SINR* threshold for successful reception. *AN*s are equipped with one transceiver, unless otherwise noted, and a sensing module.

The margin to mitigate interference to *MS*s is set at *x=40μs*, following the discussion in Sec. IV. In addition, for these experiments we used *τ=5μs* for sensing the *PRI* activity. Overall, $x+\tau \leq 60\mu s$, thus *at least 89%* of the *PRI* slot duration left unutilized available for *ASN* traffic.

For the rest of the performance evaluation, we consider the variant of *AS-MAC* without the *RES* message (*AS-MAC*$_2$). We explain these design choices in App. 1. *AN*s transmit each packet to a randomly selected neighbor. Unless stated otherwise, we evaluate *ASN* in saturation conditions, that is, with each *AN* always having a packet, with payload of *280* bytes, to transmit.

There are *C*=*8 PRI GSM* channels in use within the cell, with one of them fixed as the *ASN* control traffic and the remaining *7* channels for data traffic. The *PRI* traffic (voice calls) occupy one time slot every frame on the allocated uplink and the downlink. Calls arrive according to a Poisson process with aggregate rate *λ,* and call holding times exponentially distributed with mean *1/μ*. Typical values of *1/μ* are in the order of minutes [14]. Each new call is allocated randomly to an unavailable slot. We vary the call arrival rate to generate *GSM* loads, or percentages of utilized slots we denote as *PRI Utilization* or PRI_U, with average values of *12.5%*, *25%*, *50%*, *75%*, and *87.5%*, calculated throughout the simulation duration (*600 sec*).

We evaluate the following metrics:

(a) *Available Bandwidth Utilization*, *BU*, the fraction of the number of slots, across all *ASN* data channels, utilized by *ANs*, over the number of slots left-unused by the *PRI.*

(b) *Spectrum Utilization Improvement*, $SUI = (PRI\_ASN_U - PRI_U)/PRI_U$, where PRI_U is the % of utilized slots, across all *PRI* channels, when the *PRI* is deployed alone, and PRI_ASN_U is the *%* of slots utilized when both the *PRI* and *ASN* are deployed.

(c) *ASN Throughput*, *S*, in *Kbps* at the data link (*AS-MAC*) layer.

(d) *ASN Delay*, *D*, in *sec*, measured as the average of the periods of time from the point a packet is at the head of the *AS-MAC* sender's queue till it is delivered (including possible retransmissions).

BU quantifies the efficiency of *AS-MAC* in utilizing the available resources, while *SUI* provides the overall picture of utilization effectiveness. Note that both metrics are independent of the *ASN* physical layer (*PHY*) and thus can serve as a benchmark for any *ASN PHY* implementation. *S* reflects the *PHY* data rate, in conjunction with the utilization efficiency and the available resources. Here we assume for illustration purposes the *ASN PHY* data rate to be equal to the *GSM PHY* rate. This assumption provides with results that can be used as a *benchmark*. Nevertheless, *PHY* protocols other than the *GSM* one could be used by *ASN*s. This would provide higher *ASN PHY* data rates, and thus higher throughput. Finally, *D* probes further into the *AS-MAC* performance, allowing us to further quantify the impact of *PRI-SEC* interactions. All the data points shown below with *95%* confidence intervals are the averages over at least five randomly seeded runs.

Figs. 9, 10, and 11 show the *BU* and *SUI* metrics as a function of PRI_U, for the single-hop, grid, and random multihop topologies respectively. In all three cases, the *ASN* nodes operate in saturation conditions. In single-hop *ASN*s (Fig. 9), *BU* is up to *75%*, or, in other words, *three out of four* available *PRI* slots are utilized for *ASN* data communication. Then, in Figs. 10 and 11, *BU* is up to *179%* and *132%* for the grid and the random multihop *ASN*s. *BU* exceeds *100%* as in multi-hop topologies a single idle *PRI* slot can be in principle utilized for two or more simultaneous *ASN* transmissions. The degree of the available bandwidth spatial reuse depends on the *AN*s transmission and sensing range, as well as the multihop topology characteristics. The grid topology diameter and density higher and lower respectively, compared to those of the *100*-node random topology, thus, *BU* is higher in the former case.[7] Furthermore, in all three figures, *BU* remains practically constant as PRI_U increases, showing that *AS-MAC* remains efficient both when a significant or a small portion of the *PRI* resources are available.

SUI in Figs. 9, 10, and 11 decreases as PRI_U increases, with values ranging from *250.3%* to *5.37%* for the single-hop *ASN*, from *594%* to *15.6%* for the grid, and from *418%* to *10.5%* for the random multihop topology. Essentially, *SUI* shows the marginal improvement from deploying an *ASN*, as a function of the *PRI* load. As PRI_U increases, the resources available for the *ASN* communication decrease, thus, the additional utilization offered/achieved by the *ASN* is, unavoidably, bounded from above by $100\text{-}PRI_U$. Nevertheless, when PRI_U is low, *AS-MAC* realizes the benefits of bandwidth sharing.

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[6] Note that *AN* pairs such as the one marked by (*1*) in Figure 8 cannot cause interference due to *ASN* carrier sensing. *AN*s further away can possibly cause interference, yet as the distance of separation increases, their 'contribution' becomes negligible.

[7] Note that considerations such as the multihop network capacity, with the number of nodes increasing, e.g., discussed in [23] are beyond the scope of this paper.

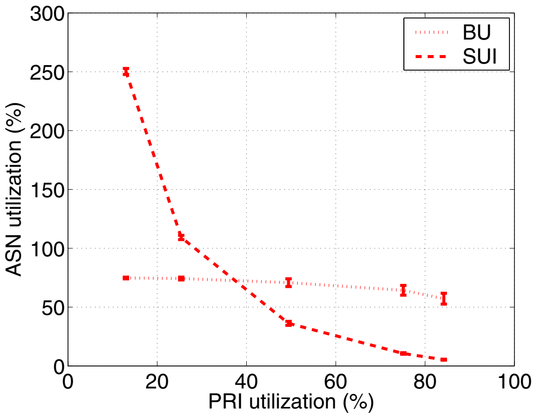

Figure 9. ***20*-node single-hop *ASN*: Utilization Performance as a function of *PRI* utilization (load).**

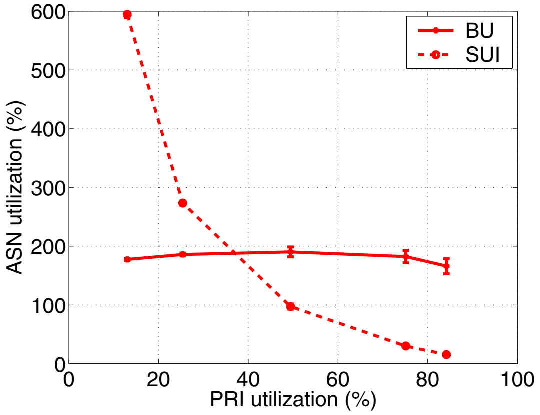

Figure 10. ***10-by-10* grid *ASN*: Utilization Performance as a function of *PRI* utilization (load).**

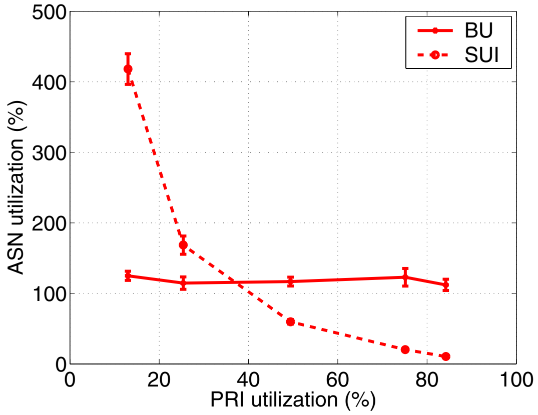

Figure 11. ***100-node* random multihop *ASN*: Utilization Performance as a function of *PRI* utilization (load).**

Figure 12 and Figure 13 show the throughput and delay achieved by the grid and random multi-hop topologies under saturation conditions as a function of the *PRI* utilization. It is seen that *AS_MAC* achieves as much as *2100Kbps* of throughput while grid achieves *1562Kbps* when *PRI* utilization is *13%*. Regarding delay, it is seen that there is not much difference between the grid and the random networks. The reason is that the packet delay at *AS_MAC* is mainly composed of the packet transmission time (another component is the delay between sending *RTS* and receiving *CTS* and is expected to be much smaller than the packet transmission time), which depends only on the profile of free slot availability (the same for both the grid and the random networks).

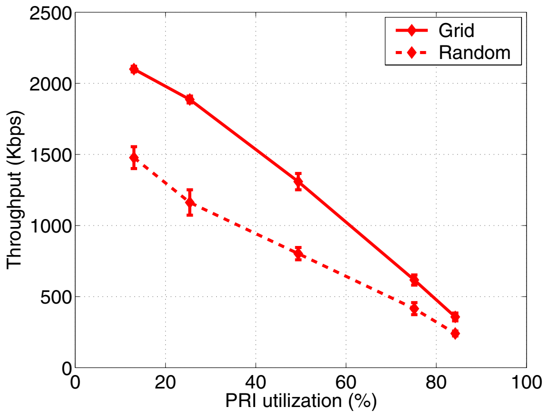

Figure 12. ***ASN* Throughput performance under saturation as a function of *PRI* utilization for 10 by 10 grid and 100-node random multi-hop networks.**

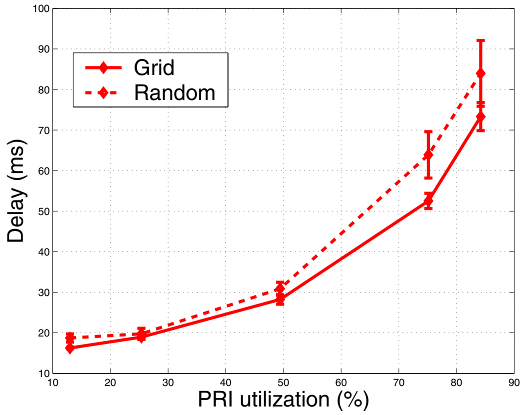

Figure 13. Packet delay at *AS_MAC* at saturation as a function of *PRI* utilization for grid and random networks

VI. DISCUSSION AND FUTURE WORK

Figure 14 is a trace showing how the throughput *S* of *ASN* (*Kbps*) varies with time for the 10-by-10 grid when *PRI* offered load is set to *50%*. Moreover, B_c and B_d, the available bandwidth on the control (*CC*) and the data channels (C_d) is shown, in *Kbps*. At *t=30sec*, there is a sharp increase in *S* because of a corresponding increase in B_d. A similar peak occurs at *t=38secs*. At *t=62secs*, B_c is very low, leading to a low *S* as well, despite the relatively high B_d. The same phenomenon occurs at *t=83secs*. It is thus evident that the *AS_MAC* performance is dependent on how B_c, B_d vary over time. Due to the dynamic nature of *PRI* traffic, low B_c degrades *S*. A solution to this problem is for *AN*s to dynamically switch to a new control channel based on the observed *PRI* load. This is possible exactly because the sensing module provides *AN*s with the *PRI* activity information. We are currently investigating the design of robust algorithms for selecting an alternate *ASN* control channel.

Next, we discuss issues related to the *ASN* transceivers. First, consider the transceiver turnaround time, that is, the period of time needed for a transceiver to switch from transmitting to receiving mode and vice-versa. In our system, such transitions need to occur at the *PRI* slot boundaries. The aggregate time of the *GSM* guard band (*15μs*), the *PRI* sensing period (*5μs*), and the margin of *27μs* to ensure negligible interference on *PRI* transmissions, is well above the *802.11g* receive-to-transmit and transmit-to-receive turnaround times of *5μs* and *10μs* for its *DHSS*.

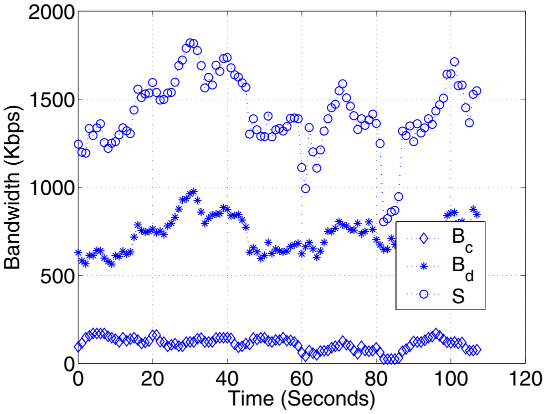

Figure 14. *ASN* throughput trace for *10-by-10* grid.

Another concern is the time needed to dynamically switch a transceiver to different channels at different points in time. In *AS_MAC* such switching needs to take place after a *RTS-CTS* handshake and after the transmission of a packet when the sender and receiver want to switch to the control channel. The channel switching time allowed in 802.11 is *224μs*. Thus it seems impractical in the near future to achieve switching times less than about *45μs*. To overcome this problem we suggest that both the sender and receiver *freeze* their operation in the next slot (irrespective of whether it is free or not) after the *RTS-CTS* handshake and resume the protocol operation thereafter. This allows ample time (at least a full slot duration of *577μs*) to switch the transceiver to the chosen data channel.

ANs can potentially receive multiple *FCCH* messages on different beacon frequencies from different *BS*s. This means that the *AN* has the freedom to choose any one such beacon frequency and use the resources associated with it. Nevertheless, *AN*s need to be provided with the criteria to make such selection. A plausible solution would be to 'tune into' cells according to the received signal strength from each beacon (i.e., *BS*), in decreasing order. Then, to enable inter-cell communication, a subset of the *AN*s will have to tune to multiple cells and act as *gateways* (*GAN*s). Even though tuning to different cells can be done alternately, using a single transceiver, such a design would entail protocol complexity. Our preliminary analysis clues that having *GAN*s tuning to two cells (assuming a hexagonal *PRI* cell layout) suffices to provide inter-cell connectivity. Thus, we consider the use of two transceivers to allow tuning to two cells simultaneously, an approach that increases admittedly hardware complexity but simplifies the protocol operation and enhances robustness. We will be presenting the details of this design, which will also entail a modification at the overlying routing protocol tables to include a network interface identifier, along with its evaluation, in future work.

We now discuss about the *PRI-SEC* service agreement needed for *ASN* to operate. For every identified cell *ASN* needs to know whether the *PRI* allows sharing its unutilized resources within that cell. We advocate that *PRI* provide such information to *SEC* in an off-line manner, in the form of a service agreement. As there could be multiple providers with each provider operating a large number of cells (or *BSs*), a mapping needs to be stored in *ANs* as to the identity of the cells that allow an *AN* to share a *PRI*'s resources. This mapping can be stored in each *AN*, with each entry being identified by the *CGI*. Service agreement is one of the policy issues currently under discussion within regulatory bodies [22].

Finally, in the discussion above, we assumed that the base and mobile stations do not utilize frequency hopping (*FH*) techniques, i.e., communication does not take place alternately over a pseudo-random sequence of channels chosen among those available. The challenge in employing *AS-MAC* with a *FH PRI* lies in that selection of the most preferable channel becomes hard. This could degrade performance for *AN*s, if an highly loaded channel is selected while other channels are relatively less loaded with *PRI* traffic. A plausible approach would be to increase the sampling period over which the channel occupancy is estimated. If $n \leq |C|$ is the number of channels used by call (i.e., the number of channels *BS* and *MS* hop across), then sampling over *N PRI* frames, with *N* a multiple of *n*, could yield an accurate estimate. Clearly, this sampling duration has to be less than the *PRI* call holding time; e.g., for $|C|=8$, $n=|C|$, and $N=10n$, sampling over approx. *370 ms* is well below the average call holding time. We will be evaluating the effectiveness of different estimation techniques and the required length of the sampling period in our future work. Another aspect related to *FH* is that aborting an *ASN* transmission is not necessary when a data channel becomes fully occupied by the *PRI*, as slot occupancy will change on a frame basis.

VII. RELATED WORK

A small number of proposals in the literature have considered *PRI-SEC* systems. Two models of *PRI-SEC* interaction are introduced in [3]: the *PRI* is aware and attempts to accommodate the traffic of the *SEC*, or the *PRI* has full priority and has no knowledge about *SEC*, and it is the responsibility of the *SEC* to ensure that unacceptable interference is avoided. The latter model is the one considered here. These two models propose spectrum pooling between a *GSM PRI* and an OFDM-based WLAN adopting the *HIPERLAN* standard [12] for the *SEC*. Our work is significantly different, as we develop an ad hoc *SEC* system that operates without fixed infrastructure. Moreover, we address a number of architectural considerations regarding the interoperation with the *PRI GSM*, such as the *SEC* traffic transmission; for example, it is not clear how the *2ms HIPERLAN* frames correspond with the *GSM* slot width of about *0.5ms*. Moreover, our design has the advantage it is not strongly dependent on the physical layer.

Finally, [13] proposes two medium access control protocol designs for a single channel *PRI-SEC* configuration, assuming that the system has the capability to predict "spectrum holes" which are then used to transfer packets. Beyond the different *PRI-SEC* configuration we consider, our work is not dependent on the prediction of resource availability and thus ensures non-interference between *PRI* and *SEC* to the extent that *ANs* are properly able to sense the spectrum. Moreover, ours is a multi-channel system.

Beyond the *PRI-SEC* context, a number of *Multi-Channel MAC* (*MMAC*) protocols were proposed. However, those are either inapplicable or inefficient and thus impractical in the *PRI-SEC* setting. [7], [8], [9] require that each node is equipped with a number of transceivers equal to number of channels, a clearly impractical assumption. [11] requires three transceivers, while a solution with two transceivers with one of them tuned constantly on the control channel to provide an up-to-date picture of the channels' state was proposed in [5] which uses an additional *RES* control packet. We have shown that *RES* is not beneficial in the presence of sensing, thereby reducing control overhead.

The asbsence of upto date channel status information is denoted as the *MHTP* when the protocol operates with a single transceiver and thus alternates between data and control channel transmissions. A solution that alleviates this problem with the requirement that nodes are synchronized is presented in [6]. However, in a multihop setting, as is our *ASN*, the absence of synchronization (non-overlapping *802.11 ATIM* windows) renders the scheme unusable. Finally, [10] proposes a single transceiver *MMAC* protocol, which addresses the *MHTP* at the expense of network performance. Nodes sense the targeted channels for a period of time equal to the maximum-size frame transmission; if an ACK is received (with *ACK*s transmitted on the control channel rather than the data channel), or if the time-out expires the node knows that the channel(s) in question is released and contends for it. The long waiting periods thus introduced would be highly inefficient. This would not be justified in our setting as *AS-MAC* is already robust to *MHTP* due to the presence of sensing.

We also briefly note that *PRI-SEC* systems are fundamentally different from data-over-cellular services, such as *CDPD* [16] or *GPRS*. In these cases, the data transmission is actually undertaken by the *PRI* system while in our case *ASN* has to provide its service without any help from *PRI* and as such is much more challenging. *PRI-SEC* systems are also fundamentally different from ad hoc extensions of cellular systems, that is, systems that allow *MSs* to form multi-hop paths to reach the *BS* (or an alternative *BS*) [21].

VII. CONCLUSIONS

This paper is concerned with the efficient utilization of the resources (spectrum) of deployed wireless communication systems, based on a bandwidth sharing approach. The basic idea is to deploy a *secondary system (SEC)* that dynamically and transparently operate only over the resources left unutilized by the licensed user of the spectrum, the *primary system (PRI)*. We proposed the *AS-MAC* protocol as the focal point of an architecture with a *GSM* cellular system being the *PRI*, and an ad hoc network being the *SEC*. Our *AS-MAC* is shown to efficiently utilize the available resources, with a utilization factor from *75%* to *180%*, due to spatial reuse in the latter case. In spite of a number of technical issues whose solution we outline here and currently investigate, we believe that approaches such as the one proposed here based on *AS-MAC* can efficiently utilize available spectrum and lead to practical deployment of secondary wireless peer-to-peer and mesh networks.

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APPENDIX

The sensing module, a parameter not previously used in *MMAC* protocols, motivated us to consider and evaluate variants of handshakes for medium access. Also we investigate how sensing affects the performance when both one and two transceivers are used at *AN*s (traditional *MMAC* designs are based on two transceivers). Since these aspects are not strictly dependent on the randomness of the *PRI* traffic, we used a static slot occupancy model for the *PRI*. Our conclusions in this regard are expected to hold for ordinary *MMAC* protocols (i.e. without any *PRI* traffic) as well.

Here the *PRI* traffic occupies a fixed number of time slots in every frame on each data channel, and similarly for the control channel with a different number of free slots. We vary the *%* of available slots in the control and data channels, with values from *25%* (*2* out of *8* slots per *GSM* frame) to *100%* (*8* out of *8* slots), denoting the % of available slots in each control and data channel as B_C and B_D. We use this scenario to investigate such properties of our *AS-MAC* design that are expected to hold for ordinary *MMAC* protocols as well. We show the performance of the two versions of *AS-MAC* we discussed, *AS-MAC*$_1$ and *AS-MAC*$_2$.

Figure 15 shows *BU* when $B_d = 25\%$ and *50%*, as a function of B_c. Note that the two schemes require different control overheads (*33%* less for *AS_MAC*$_2$). Also a *RTS-CTS* (*-RES*) handshake is necessary for every data packet. Thus B_c can be a potential bottleneck and plays an important role in protocol performance. So we chose to plot the performance against B_c.

We do not take the control channel bandwidth into account in these calculations. In that case, the spectrum utilized by *ASN* would be slightly less than what our graphs indicate, yet the trends will remain the same.

We observe that for lower values of B_c *AS_MAC*$_2$ performs the best as it needs less control bandwidth since it does not use *RES*. But as B_c is increased beyond about *60%*, *AS_MAC*$_1$ starts performing better than *AS_MAC*$_2$ as the control bandwidth is no more a bottleneck and the additional *RES* that *AS_MAC*$_1$ uses brings in some benefits. But even when the available control bandwidth is *100%*, *AS_MAC*$_1$ performs only marginally better than *AS_MAC*$_2$. In Figure 15, the comparison between *AS_MAC*$_1$ and *AS_MAC*$_2$ goes as *233.2%* to *225%* when $B_d = 25\%$ and *201%* to *188%* when $B_d = 50\%$. This means that the use of the additional *RES* control packet is not very useful (when multi-channel sensing is present).

A natural question that now arises is how useful is *RES* when multi-channel sensing is absent. The results of this scenario are shown in Figure 16. “*NS*” in the legend refers to no sensing being used. “1Tx” means *ANs* are equipped with only one transceiver and “2Tx” means they have two transceivers with one of them permanently listening to the control channel which enables the *AN*s to receive the *CTS* and *RES* packets from neighboring *AN*s effectively. It is seen that when sensing is absent, *AS_MAC*$_1$ performs better than *AS_MAC*$_2$ (*52.8%* to *33.6%* for 1Tx and *131%* to *53%* for *2Tx*). The difference is much more pronounced for the “*2Tx*” as now the control packets are being received effectively. In the absence of sensing, *ANs* are fully dependent on *CTS* and *RES* packets for knowing channel status. When control packets are ignored, nodes end up choosing already busy channels leading to excessive collisions. This confirms that *RES* is important when sensing is absent but not so otherwise.

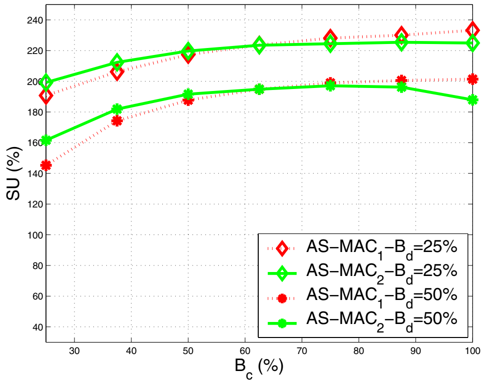

Figure 15. % *BU* when $B_d = 25\%$ and 50%, Vs B_c

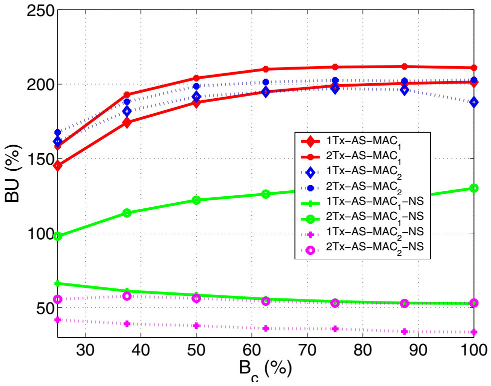

Figure 16. % *BU* vs. B_c when one or two transceivers are used in the presence and absence of sensing, and $B_d = 50\%$

Figure 16 also shows how the presence of sensing helps mitigate (Multi-channel hidden terminal problem) *MHTP* [6]. When *ANs* use only one transceiver (“*1Tx*”) they suffer from *MHTP*. It is seen that the performance degradation due to *MHTP* when sensing is present is much less (*211%* to *201%* for *AS_MAC*$_1$, and *203%* to *188%* for *AS_MAC*$_2$), while as seen before the performance degradation is much more pronounced when sensing is absent. This illustrates that sensing makes the protocol robust to *MHTP*.