SPECTRUM SENSING IN THE VEHICULAR ENVIRONMENT: AN OVERVIEW OF THE REQUIREMENTS

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ABSTRACT

This paper overviews the challenges related to spectrum sensing in the vehicular environment, with emphasis on sensing in the TV licensed band. In the vehicular environment the cognitive radio can help to: 1) satisfy capacity demand for Intelligent Transportation Systems (ITS) applications; and 2) offload time insensitive applications from the ITS dedicated spectrum. However, neither sensing, nor geolocation database lookup alone can provide sufficient incumbent protection. Collaboration among the sensors to take advantage of spatial diversity is difficult due to the rapidly changing network topology. Nevertheless, mobility provides the opportunity to use time diversity at each sensor. We also discuss the influence of sensing subsystem design on the vehicular cognitive network medium access (MAC) sublayer. Whenever applicable, we compare sensing requirements for vehicular cognitive networks to the requirements provided in the IEEE 802.22 standard.

1. INTRODUCTION

Opportunistic utilization of scarcely used spectrum is seen as the way to provide bandwidth that can accommodate continuously increasing number of wireless applications. The TV broadcast band appears to be the "perfect" candidate for this purpose due to low utilization (in particular in rural areas) [1], combined with favorable propagation characteristics which provide relatively long range in comparison to higher frequency bands.

Recent efforts to exploit TV white space are progressing in two directions. On the standardization side IEEE 802.22 wireless regional area networks (WRAN) targeting rural areas [2] was published in July 2011. Other standards are in different phases of development [3] [4] [5] [6] [7] [8]. Recent examples of the implementation efforts are [9] and [10]. Typical applications are Internet access in remote rural areas and remote utility meter reading.

In this document we discuss some of the system engineering issues related to spectrum sensing in the vehicular environment, with emphasis on sensing in the TV licensed band. Although the vehicular environment, due to mobility, introduces significant implementation challenges, we believe that the cognitive radio in this environment can serve twofold purpose: 1) to satisfy capacity demand for Intelligent Transportation Systems (ITS) applications; and 2) as an aid to offload the time insensitive ITS applications from the dedicated spectrum.

The cognitive network nodes must be aware of the spectrum holes in order to utilize them. The two approaches being considered for spectrum awareness are incumbent user signal sensing and geolocation database lookup. We discuss advantages and drawbacks of both approaches and argue that none of them separately can provide sufficient primary user (PU) protection from interference created by vehicular cognitive networks. To corroborate this claim we provide examples in which either one or both of these methods fail.

In the research community collaboration among the sensing nodes, which exploits spatial diversity, is seen as the way to alleviate requirements on PU detection sensitivity [11]. Although mobility causes difficulties in implementing collaboration, it also introduces temporal diversity. Since reliable and timely fusion of sensing information is challenging because of rapidly changing network topology, we argue in favor of utilization of temporal rather than spatial diversity.

We also discuss the influence of sensing subsystem design on the medium access (MAC) sublayer of the vehicular cognitive network protocol stack. This includes: 1) scheduling of quiet periods for sensing; 2) exchange of sensing information among collaborating nodes; 3) coexistence with other cognitive networks of the same or different type; and 4) rules to establish and maintain connection, and to deal with disruptions in connectivity.

In the following, whenever applicable, we compare sensing requirements for vehicular cognitive networks to the requirements provided in the IEEE 802.22 standard.

In Section 2 we motivate our interest in cognitive radio applications for the vehicular environment. Section 3 addresses the issues with sensing and geolocation database lookup under high mobility. Section 4 treats the time diversity. Influence of sensing on the MAC design is addressed in Section 5. In Section 6 we point out some issues related to differences in regulatory domains. Section 7 concludes the paper.

2. PURPOSE OF THE COGNITIVE RADIO IN THE VEHICULAR ENVIRONMENT

In this section we first argue that the current spectrum assigned for ITS applications is not sufficient. The first step to overcome the spectrum shortage is to use the TV white space to offload time insensitive applications like travel advisory from the ITS dedicated band, and consequently provide more bandwidth for delay intolerant applications.

Second, the cognitive radio can provide alternative to ITS traffic safety and information applications in the dedicated bands, provided that channel switching when a primary user is detected is performed sufficiently fast.

Third, from the perspective of the radio waves propagation, any infrastructure–to–vehicle (I2V) service would benefit from the extended range in the TV bands in comparison to the 5.9 GHz band. Many studies point out difficulties in maintaining WiFi connectivity in the vehicular environment because of small cell radius and wired infrastructure limitations [12] [13] [14].

2.1. ITS Spectrum Scarcity

The dedicated short range communication (DSRC) is introduced to improve safety, enhance travel experience, and even provide access to Internet. In the USA it utilizes seven 10 MHz channels around 5.9 GHz [15] and allows for bitrates ranging from 3 Mb/s to 27 Mb/s. It is based on the carrier sense multiple access with collision avoidance (CSMA/CA) 802.11–like MAC, labeled 802.11p. It is reasonable to assume that, due to the protocol overhead, only a half of the designated rates represent the actual goodput. In other words, the users benefit from a half of the spectral efficiency, which is between 0.3 bit/s/Hz and 2.7 bit/s/Hz. The available bandwidth is shared between a variable number of users. Assignment of one 10 MHz channel exclusively for vehicle–to–vehicle (V2V) communication is under consideration [15].

The protocol analysis provided in [16] considers one-dimensional array of stationary vehicles with variable density. In such a configuration, given a typical sedan length, the maximum density is 200 vehicles per kilometer, or one vehicle every 5 m. The protocol fails to deliver 90% of packets, even in the case of short 200 byte messages and arrival rate of only 2 packets per second per node. Of course, further performance degradation is expected on a multilane highway with mobile terminals because of increased number of nodes and time-varying radio channel.

The authors of [17] consider similar one–dimensional topology, and propose a dedicated transmission queue for time critical safety information. With this modification the allowed number of message retransmissions becomes the key parameter in providing reliability. A wrong setting can have detrimental effect on the packet delivery rate. Too small value results in a low delivery rate, and too large value causes network saturation.

In Japan, the Association of Radio Industries and Businesses (ARIB) standardized under code T75 a physical (PHY) layer in the 5.8 GHz band, which is different from DSRC PHY in the USA [18]. It is designed to provide range up to 30 m across seven pairs of 5 MHz uplink and downlink channels, each pair separated by 40 MHz. The channels support 1 and 4 Mb/s. The primary purpose of the system is electronic toll collection (ETC) and travel assistance. In addition to 70 MHz in the 5.8 GHz band, supplementary 10 MHz segment is assigned for ITS applications between 755 and 765 MHz [19].

2.2. Emerging Vehicular Applications

Since it is very difficult to predict which future vehicular applications will consume the spectrum, we can only provide a few examples of recent trends.

An application using speech recognition software can remotely, through voice commands, perform simple tasks like starting the car engine, opening the trunk, locking the doors, or activating the car alarm [20].

Car manufacturers consider open source hardware and software platforms as an opportunity for developers around the world to create novel vehicular applications [21]. Another example is wireless access to the controller area network (CAN) bus which connects on–board computer unit (OBU) to the vehicle sensors and actuators [22].

2.3. Propagation Advantages of the TV Band

In the free space the received power P_r as a function of transmit power P_t at distance d is

$$P_r = \frac{G_t G_r \lambda^2}{(4\pi d)^2} P_t, \tag{1}$$

where λ represents the wavelength, and G_t and G_r represent transmit and receive antenna gains, respectively. Linear antennas, like a half-wavelength dipole or a monopole, have their size (and thus the aperture) adjusted so that the gain is constant irrespective of the wavelength [23]. Using (1) it can be shown that in free space, for a fixed distance and transmit power, the received power at 5.9 GHz is almost two orders of magnitude smaller than the power at 700 MHz:

$$20\log_{10}\left(\frac{5900}{700}\right) = 18.5\,\text{dB}. \qquad (2)$$

It should be noted that this naive model neglects two important factors: 1) the intricacy of multipath propagation; and 2) diffraction, which favors lower frequencies over higher frequencies. The latter is usually referred to as the property of lower frequencies to easier "bend" around corners. Still, (2) points out general advantage of TV bands over the microwave DSRC bands: due to extended range the mobile terminal can maintain connectivity to the roadside unit for longer time. Consequently, less frequent handoff and simplified routing is needed as the cars traverse roadside units' coverage area. In addition, decreased density of roadside units results in lower deployment cost.

3. WHITE SPACE AWARENESS IN THE VEHICULAR ENVIRONMENT

3.1. Spectrum Awareness in IEEE 802.22

The IEEE 802.22 standard [2] is designed to provide wireless Internet access through a cellular–like centralized system in remote rural areas without wired infrastructure. The TV spectrum occupancy is obtained either by collaborative sensing coordinated by the base station (BS), and/or by access to a geolocation database with the channel allocation of primary users.

The maximum time interval allocated for sensing can be set between 1 and 160 ms. Channel occupancy is assessed for 30 s before establishing communication. In the USA, once the channel is declared free of incumbents and used for communication, it is reassessed at least once a minute. Whenever a primary user is detected the nodes are required to vacate the current channel after at most two seconds, and have less than 100 ms to transmit coordination messages. Sensing must be able to detect a PU in 2 s with detection probability $P_d = 0.9$, and with probability of false alarm $P_f = 0.1$. The BS performs fusion of sensing results by applying OR rule.

In the case of the geolocation lookup access to the database is required at least once in 24 hours.

3.2. Impact of Mobility on Sensing

Multipath fading occurs because many signal replicas are arriving at the sensor with different delays. In the most extreme cases severe fading can be observed when terminals move by a fraction of wavelength. In the ultra–high frequency (UHF) TV bands between 470 MHz and 890 MHz the wavelength is less than a meter. A car which is, for instance, traveling at 40 km/h (25 Mph) passes 1 m in 90 ms.

The time variations of a mobile radio channel are related to the mobile terminal speed. For a sinusoidal wave

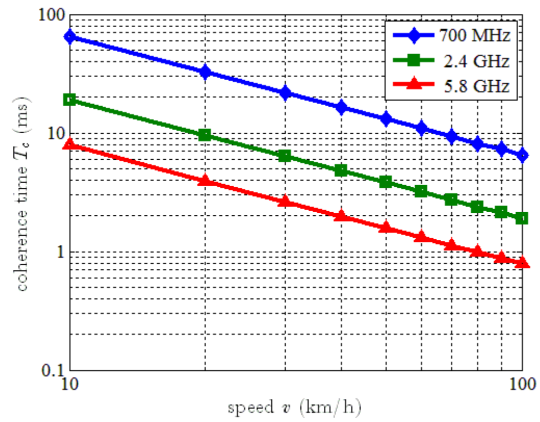

Fig. 1. Flat Rayleigh fading coherence time as a function of the mobile receiver velocity for different carrier frequencies.

of frequency f the maximum dispersion f_D in the Doppler frequency domain is directly proportional to speed v

$$f_{D\max} = \frac{v}{c} f, \qquad (3)$$

with c being the speed of light in the vacuum. The time scale of random channel variations is inversely proportional to the maximum Doppler shift [24]. For flat Rayleigh fading this relationship, which is illustrated in Fig. 1, is approximated with

$$\begin{aligned} T_c &= \frac{0.423}{f_{D\max}} \\ &= \frac{0.423 \cdot c}{v \cdot f}. \end{aligned} \qquad (4)$$

In general, at lower frequencies the channel coherence time T_c is larger and the channel appears as approximately time invariant for longer time intervals. This means that the channel estimation and tracking, as well as synchronization, are less demanding tasks for the receiver.

Even after the multipath fading is averaged in the "local area" in which its mean does not change significantly, slowly varying fluctuations can be observed. These remaining variations are frequently modeled with a lognormal random variable perturbing the median path loss. Somewhat arbitrarily these variations are termed "shadow fading" because they decorrelate with changes in sensor position on the order of the size of objects in its vicinity. The most popular simple shadowing correlation model is the one presented in [25].

In Table 1 we present comparison of the system design properties of cognitive WRANs and vehicular cognitive networks.

Table 1: Comparison of system design properties of cognitive networks.

	Cognitive WRANs	Cognitive vehicular networks
Application	Internet access	ITS, possibly Internet access
Range	~ 30 km	At most a few kilometers
Mobility	Low: stationary and pedestrian	Can exceed 100 km/h
Topology	Centralized with base station	I2V: centralized V2V: ad–hoc
Target population density	~ 5 users per km^2	Could be larger by two orders of magnitude
Propagation environment	Line–of–sight (LOS) Large delay spread Large propagation delay Slow time variations	Both LOS and NLOS are possible Rate of time variations depends on vehicle speed

3.3 Link Budget

As an example, let us consider Advanced Television Systems Committee (ATSC) digital TV broadcast signal common in the USA. The 6 MHz ATSC channel noise floor is $N_0 = -106$ dBm. In practice, the required sensing threshold for ATSC signal is set below this floor. For instance, the empirical study presented in [26] recommends the sensing threshold between $-118.5 \leq N_s \leq -108.5$ dBm, depending on the secondary user transmit power limit. In the IEEE 802.22 standard [2] it is set to $N_s = -114$ dBm.

The required sensitivity threshold results in sensing being performed under a very low signal–to–noise ratio (SNR). In [27] it is determined as

$$\rho = N_s - N_0 + G_a - N_f, \tag{5}$$

where N_f represents the sensor front end noise figure (typically 5 to 10 dB), and G_a represents the antenna gain. In the vehicular environment it is reasonable to assume a quarter-wavelength antenna positioned on the car roof with approximately 5 dB gain. Assuming 10 dB noise figure, the required SNR is −13 dB.

To accommodate for fading fluctuations the fading margin must be incorporated into (5). This can be done in two ways.

The first approach would be to start with a system model which incorporates both white noise and fading, and devise P_d and P_f. However, this must be repeated for each sensing algorithm. An interested reader can for instance find in [28] that required SNR for the incoherent matched filter detecting a deterministic signal in flat Rayleigh fading is

$$\rho_0 = \frac{\ln(P_f)}{\ln(P_d)} - 1. \tag{6}$$

This requirement can be relaxed by sensing for multiple occurrences of a known signal feature like synchronization sequence, that is, by increasing the sensing interval duration.

In a rather simple but more generic approach which is independent of the selected sensing algorithm, we can assume certain *outage probability* and lower the sensing threshold by the corresponding *fading margin*. Let us consider flat Rayleigh fading, which represents the most undesirable situation in practice, with only indirect multipath signal replicas propagating toward the receiver/sensor. Under this assumption the SNR is exponentially distributed with some mean $\bar{\rho}$. The outage probability P_0 is the probability that the instantaneous SNR will fall below the threshold ρ_0

$$\begin{aligned} P_0 &= \Pr(\rho < \rho_0) \\ &= \int_0^{\rho_0} \frac{1}{\bar{\rho}} \exp\left(-\frac{\rho}{\bar{\rho}}\right) d\rho \\ &= 1 - \exp\left(-\frac{\rho_0}{\bar{\rho}}\right). \end{aligned} \tag{7}$$

If we assume that only P_0 fraction of time the SNR should be below the minimum sensing requirement ρ_0, the average SNR must be increased by the factor [29]

$$\frac{\bar{\rho}}{\rho_0} = \frac{1}{-\ln(1 - P_0)}, \tag{8}$$

which represents the fading margin. Therefore, for 10% outage the average SNR should be increased by approximately 10 dB, and for 1% outage rate it should be increased by approximately 20 dB. Alternatively, the sensing threshold should be decreased by the same quantity. For instance, an ATSC sensor operating in flat Rayleigh fading with –23 dB SNR should be able to detect incumbent users 90% of time with 90% success rate.

3.4. Database Lookup versus Sensing

In the USA, as well as in the United Kingdom, the database lookup is accepted as the primary method for spectrum awareness [30] [31]. A location aware secondary user is

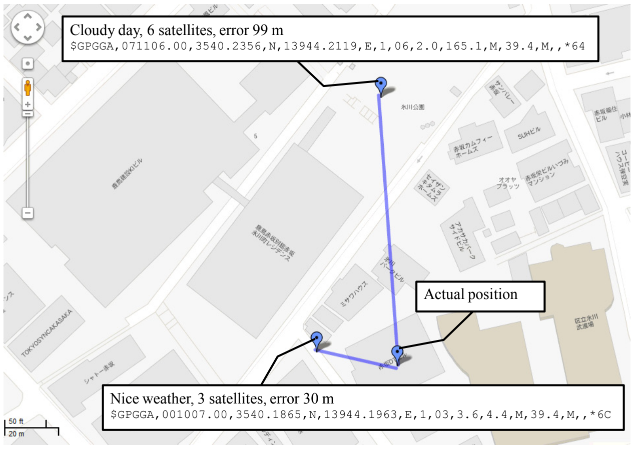

Fig. 2. Example of GPS localization accuracy.

required to periodically access the database of available white space. Although this solution seems very attractive given that it is much simpler than sensing (and in particular cooperative sensing), this approach is not without drawbacks.

First, the secondary user must be location aware. This typically assumes that it has attached a Global Positioning System (GPS) receiver. Alternatively, IEEE 802.22 allows for sophisticated ranging techniques to be used in order to determine user device locations.

Having a GPS receiver device does not guarantee that the secondary will have accurate position at all times. The accuracy depends on the signal strength which deviates with the cloudiness and amount of water vapor in the atmosphere as well as with shadowing due to trees, buildings, etc.

To illustrate the issues with accuracy we put an Ettus Research Universal Software Radio Platform (USRP) N210 [32] equipped with a GPS driven oscillator (GPSDO) [33] on the roof of a building, and measured coordinates on two occasions: during a cloudy day and when the sky was clear. The results in Fig. 2 illustrate that accurate location can be determined with only three satellites when the weather is favorable. When the weather is rainy even six satellites result in an error which exceeds the 50 m geolocation accuracy requirement of FCC [30] by almost 100%. The IEEE 802.22 requires that the location should be determined within 100 m with 67% reliability [2]. In both documents a mobile user is required to perform database query whenever it moves more than 50 m.

The need for Internet access in order to query the database can cause "chicken and egg" problem whenever the secondary users are actually looking for white space in order to access Internet. Centralized network topologies are less prone to this problem, because the base stations, acting as the gateway to Internet, can query databases and obtain spectrum occupancy charts. Since the base stations are fixed, their coordinates can be determined accurately during the commissioning phase. The clients can then simply listen to the BS beacons and associate on the advertised channel. An

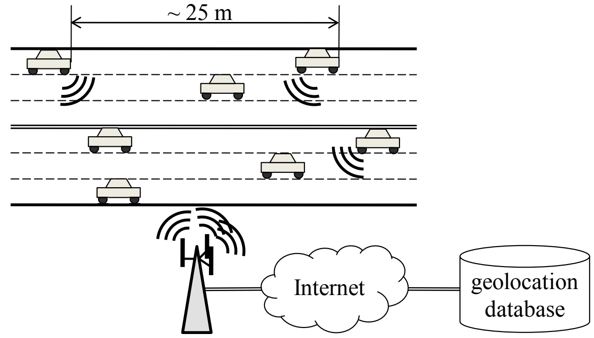

Fig. 3. Probing of the geolocation database in the vehicular environment.

ad–hoc V2V network must have additional wireless connection to access the database and means to distribute spectrum occupancy between peer nodes.

Sending a database query over Internet involves a variable round–trip delay. To handle this delay Ofcom initially required that the database must reply to the secondary users in ten seconds. This requirement is currently under consideration and it might be abolished [31]. In the vehicular environment a similar restriction would be very important, since a mobile terminal can significantly change position before the response arrives. For a car traveling at 100 km/h this means that the occupancy information is obsolete by current FCC rules if it arrives later than 1.8 s because by that time the vehicle already moved more than 50 m.

To illustrate possible problems with database access congestion, let us assume a six–lane freeway as in Fig. 3. Let us also assume that a 10 km section of the freeway is covered by a single mobile communication system cell. At 100 km/h and heavy traffic involving one car in a lane passing every second, the average distance between the cars is approximately 25 m. Consequently, there are 2400 vehicles in the 10 km section.

If the rules given in [2] and [30] are adopted for vehicular networks, a car traveling at 100 km/h would create one database query every 1.8 s. This means that the considered base station must deal with more than 1300 queries per second in addition to already existing data and voice traffic.

3.5. Examples of Spectrum Awareness Failures

In some situations the sensing, the database lookup, or both can fail.

3.5.1. Sound Barriers

Sound barriers are used to reduce noise in settlements which are close to roads with heavy traffic. However, they can also conceal primary transmitters low on the horizon (Fig. 4) and

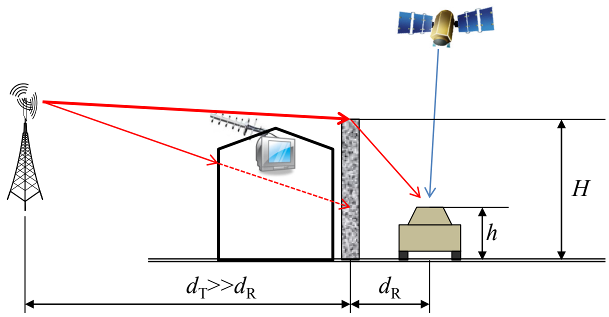

Fig. 4. Geometry of the primary user signal diffraction over the sound barrier.

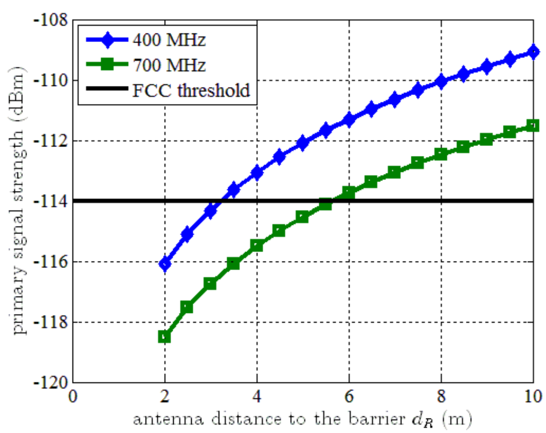

Fig. 5. Primary signal strength as a function of distance from the sound barrier for $H = 5$ m and $h = 1.5$ m.

create a classic hidden node problem. We assume that the PU signal cannot penetrate through the adjacent buildings and the barrier.

In such a case the signal strength at the sensor can be determined from a simple knife edge diffraction model [24]. Since $d_T >> d_R$, the Fresnel–Kirchhoff diffraction parameter κ is [34]

$$\kappa = (H - h)\sqrt{\frac{2(d_T + d_R)}{\lambda d_T d_R}} \approx (H - h)\sqrt{\frac{2}{\lambda d_R}}, \quad (9)$$

For κ > 1 the diffraction loss is approximately [34]

$$P_{\text{diff}} = 20\log_{10}\left(\frac{0.225}{\kappa}\right), \quad (10)$$

with less than 1 dB error.

Let us assume a TV set positioned in a house in front of the sound barrier with 7 dB noise figure and six–element

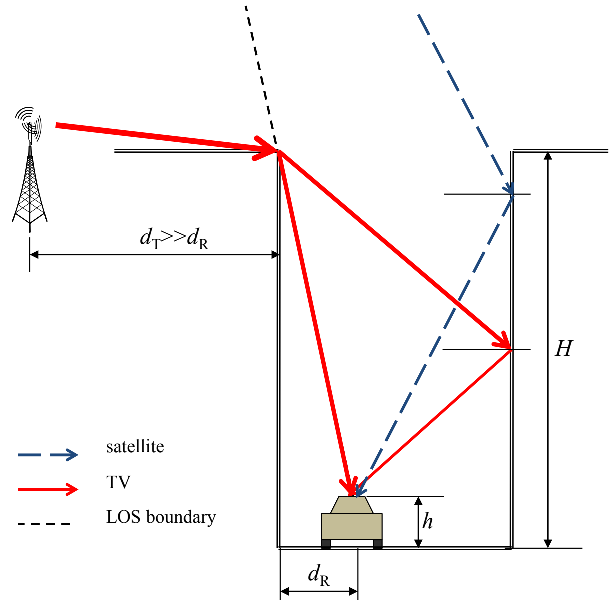

Fig. 6. Urban canyon propagation geometry.

Yagi–Uda antenna with 10 dB gain [23] on the roof. Since the set typically requires at least 15 dB SNR [35], the minimum signal strength at which it can operate $P_{r\,min}$ is –94 dBm:

$$P_{r\,min} = \rho_{min} + N_0 - G_a + N_f\,. \quad (11)$$

Therefore, on the other side of the barrier, depending on the distance between the barrier and the vehicle, the signal could be below the FCC imposed detection threshold (Fig. 5). At the same time, the sky above multilane freeways is usually free of obstructions and an on–board GPS device can calculate accurate position.

3.5.2. Urban Canyon

The satellite link budget is detailed in [36]. The budget takes into account the transmit power, free space path loss, atmospheric losses, user antenna gain, and polarization mismatch. The signal strength at the receiver is –130 dBm, way below the –114 dBm noise floor. In an urban canyon at 1.575 GHz the tight GPS link budged suffers from additional loss since the receiver is shadowed by buildings (Fig. 6).

In the first approximation the diffraction of the satellite signal can be neglected, and only reflection from the opposite wall of the canyon taken into account. Depending on the angle of incidence, the reflection loss can be several decibels, and can cause outage of the GPS signal.

On the other hand, the primary user signal diffracted from the canyon edge can be modeled as the superposition of the direct and the reflected ray [34] (Fig. 6). Similar to the reflected satellite signal, the reflected ray is scaled by

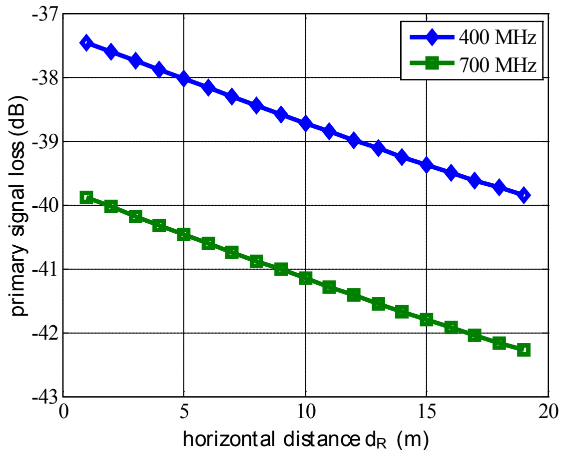

Fig. 7. Primary signal diffraction loss in the urban canyon assuming vertically polarized sensing antenna, H = 100 m, h = 1.5 m, and 20 m wide street.

the wall reflection coefficient. Although the primary signal diffraction loss (illustrated in Fig. 7) can exceed 40 dB, it can be accommodated for, depending on the TV signal strength at the edge of the canyon.

3.5.3. Tunnels

The example in which both sensing and database lookup fails is presented in Fig. 8. Usually, wireless connection is not available in tunnels. Even if the connection is available, the GPS localization cannot determine the vehicle position. One solution to this might be to use the gyro and yaw sensors within the vehicle to correct/estimate the position information when GPS signals are not available.

Spectrum sensing can correctly conclude that there is abundance of available spectrum inside the tunnel. However, once the vehicle leaves the tunnel, spectrum occupancy can almost instantaneously change dramatically.

4. UTILIZATION OF TIME DIVERSITY FOR SPECTRUM SENSING

Common engineering approach to overcome poor detection performance due to fading, described in Section 3, is to apply diversity technique. When a set of uncorrelated channel realizations is observed, it is less likely that the outage will occur on all the realizations. As more and more approximately independent realizations are taken into account, the performance of the overall system approaches (in the limit) the performance of a sensor exposed to only the thermal white noise [29]. Since the wireless channel is a function of frequency, time, and space, in the most general case all these dimensions can provide diversity:

1) Across time a single sensor repetitively searches for the primary user transmissions.
2) Collaboration is achieved across spatial dimension by exchanging information among the sensors.
3) Combined spatial and temporal diversity utilizes both of these approaches.

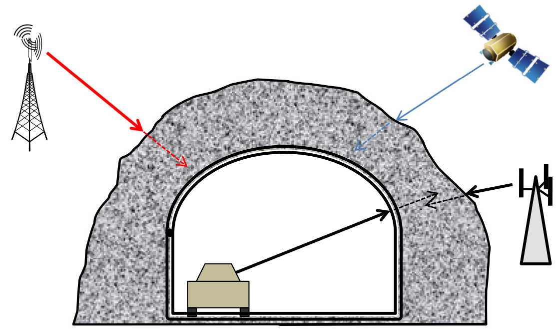

Fig. 8. In a tunnel both sensing and database lookup fail to provide information about available spectrum at the tunnel exit.

In order to satisfy the requirement for uncorrelated channel realizations the samples must be sufficiently separated in time and/or space. The channel realizations are practically uncorrelated when their separation is larger than the coherence time T_c or coherence distance D_c. These are, respectively, the time and the distance at which the magnitude of the correlation coefficient of the channel response reduces and remains below a suitable constant, typically 0.5. As the vehicle moves by an average speed v (regardless of direction in an isotropic environment) it takes

$$T_c = \frac{D_c}{v} \tag{12}$$

to traverse the coherence distance.

Provided that the data fusion can be readily performed, the advantage of spatial diversity is low latency. However, in order to aggregate sensing information, some form of communication must exist. This is difficult in the V2V case, due to the volatile nature of the network topology. This is particularly important for soft sensing algorithms, which generally require exchange of more information than hard fusion algorithms.

In [37] a slotted secondary communication with three phases is proposed: 1) sensing; 2) fusion; and 3) data communication among secondary nodes. The authors of [38] consider electing a node to take responsibility for sensing coordination. A method to select sufficiently uncorrelated spatial samples in a distributed manner is presented in [39]. Reference [40] analyzes the tradeoff between temporal and spatial diversity in a mobile environment.

Let us assume that a relevant regulatory authority requires that the sensing decision must be made every D meters or T seconds (Fig. 9). Whichever is the case, the parameters are coupled by the average sensor speed

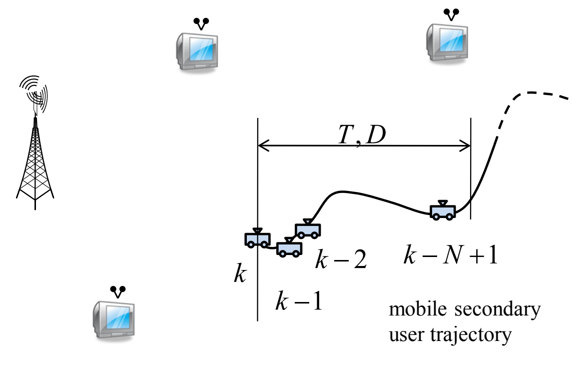

Fig. 9. Utilization of time diversity.

$$D = T \cdot v. \tag{13}$$

Inside this interval there are N uncorrelated sensing periods of duration $\Delta T < T_c$ (Figs. 9 and 10)

$$N = \left\lfloor \frac{T}{\alpha T_c} \right\rfloor = \left\lfloor \frac{D}{\alpha D_c} \right\rfloor, \tag{14}$$

with $\alpha > 1$ representing a suitably selected coherence margin.

Thus, sensing is performed for a time shorter than the coherence time, and the remainder until the next sensing period can be used for communication. The decisions made after N sensing intervals can be infrequently exchanged between the nodes to reinforce accuracy through collaboration.

The coherence time and/or distance can be coarsely estimated by means of crude geolocation information or environmental perception. For instance, the decorrelation distance D_c with typical range from 10 m to 100 m [29], can be tabulated into a handful of values, each suitable for a different terrain topography and urbanization level. The inaccuracy in estimation can be accommodated by α.

5. INFLUENCE OF SENSING ON THE MAC LAYER DESIGN

Design of the MAC sublayer and design of the sensing subsystem are tightly coupled. Sensing related activities controlled by MAC are:

- Scheduling of quiet periods for sensing.
- Selection of the sensing duration.
- Exchange of sensing related messages, including data fusion for cooperative sensing.
- Keeping track of unused available channels for backup.
- "Pushing" of spectrum availability information from the database to the end user terminals which are without sensing capability, like FCC Mode I devices [30].

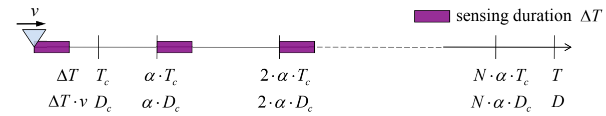

Fig. 10. Scheduling of sensing to utilize time diversity.

Sensing design is greatly influenced by the network architecture. In a vehicular environment the centralized architecture is usually associated with the I2V scenario. A V2V network connects a *swarm* of vehicles on the road which travel in the same direction with similar speeds. Such a network is more likely to be ad–hoc due to volatile routes. From the perspective of protocol design, and in particular sensing, centralized architectures offer many advantages:

- *Quiet period synchronization*: The BS is responsible for traffic management and quality of service (QoS). Thus, it can also order nodes to cease transmissions during sensing periods.
- *Sensing information fusion*: In collaborative sensing the information gathered by all sensors: 1) must be aggregated; 2) a decision about the presence of the primary user must be reached; and 3) the decision must be distributed to all secondary users. In a centralized network it is natural to assign these roles to the BS.
- *LOS propagation*: BSs (or RSUs) are usually positioned with careful planning to provide optimum coverage. BS antennas are mounted on towers which provide line–of–sight (LOS) propagation. This also makes sensing task easier.

In the vehicular environment these tasks must be distributed between the nodes. The nodes must be able to agree on quiet periods for sensing, as well as to perform data fusion in a temporally unstable topology.

6. STANDARDIZATION AND REGULATORY DOMAIN ISSUES

Crude geolocation information is required for a vehicular cognitive device irrespective whether it uses database lookup or active sensing to discover spectrum opportunities. This information is needed to determine regulatory domain (a country or a region) in which the device is located for the following reasons:

- In different regulatory domains different bands might be available for white space utilization.
- Even if the same band is used, the primary users can occupy channels of different width. For instance, the TV channels across regulatory domains could be 6, 7, or 8 MHz wide.
- Communication systems deployed in the same band and on the same channel in different regulatory domains can vary significantly with respect to the employed standard. Analog TV standards are NTSC, PAL and SECAM. Widespread digital standards include ATCS, DVB, and

ISDB–T. Unless the sensing algorithm falls in the class of so called blind algorithms, its design depends on the distinctive features of the signal. For instance, presence of the distinctive pilot tone is characteristic for ATSC signal, the DVB-T signal includes pilot symbols, etc.

- Even for the same technologies in the same band the sensing requirements could be different in different countries. For instance, in IEEE 802.22 sensing is optional in the USA, and not required in Canada [2].
- The design of vehicular MAC can be different across regulatory domains.

7. CONCLUSION

We presented some system design concerns related to the utilization of white space in the vehicular environment. Although the vehicular environment poses many implementation challenges, we conjecture that the ITS licensed spectrum scarcity makes the deployment of vehicular cognitive networks inevitable. Through a handful of realistic scenarios we show that neither spectrum sensing, nor geolocation database lookup alone can provide sufficient protection for incumbent users. While collaboration between the sensors is usually recognized as the method to improve sensing performance, we believe that due to mobility of the nodes, use of temporal diversity must have precedence over collaboration.

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