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Cognitive Cellular Systems within the TV Spectrum

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Abstract— **We propose a network architecture that enables spectrum sharing between a primary TV broadcast system and a secondary cellular broadband system. To compensate for the interference caused by overlay transmissions, the cognitive cellular base station cooperates with the TV system. We base our encoding approach on prior theoretical results and demonstrate how the cognition can be enabled in the TV spectrum. We show the performance gains of the proposed overlay approach for both the downlink and uplink of the cellular system. While the proposed approach requires that a cellular base station spends a part of its power to cooperate with the TV system, at the same time, it opens up frequency bands with favorable propagation properties, otherwise unavailable to cellular systems. This approach can thus bring benefits to both cellular and TV network operators in terms of performance and increased capacity.**

Keywords- *cognitive radio channel, dynamic spectrum access, spectrum sharing, cooperative communications.*

I. INTRODUCTION

The wireless spectrum is used by a variety of different services, including, terrestrial wireless communication systems, satellite communication systems, radio astronomy, broadcasting services or radio navigation. In recent years, cellular networks have transitioned from providing mobile telephony with limited data to supporting universal mobile broadband services. This has led to a large capacity demand that cannot be accommodated within the spectrum resources allocated to these systems. The spectrum demand for mobile communication systems by the year 2020 has been predicted by the International Telecommunications Union (ITU) to be on the order of 1280–1720 MHz [1]. In contrast, the total amount of spectrum currently occupied by or recommended for mobile communication is around 230–430 MHz, depending on the geographic region [2]. At the same time, it has been shown that in many frequency bands the spectrum resources are not always efficiently used [3]. This motivates new paradigms of spectrum allocation that enable more dynamic and flexible spectrum access to be investigated by regulatory and standardization bodies (see e.g. [4]). One approach to dynamic spectrum access is to allow *secondary systems* to access spectrum resources that have been allocated to a primary system, under the obligation that the secondary usage does not harmfully interfere with the primary service.

Three different approaches to primary-secondary spectrum sharing have been investigated: *underlay, interweave* and *overlay* operation [5]. In the underlay approach, the secondary system transmits at a signal level that is below an interference level (often called interference temperature, see e.g. [6]) and is close to the noise level; thereby the secondary transmission remains mostly unnoticed by the primary system. This approach is typically used in local short-range ultra wideband systems. In the interweave approach, the secondary system determines *spectrum holes* or *spectrum white spaces* in time, frequency and/or geographic location that remain unused by the primary system. This strategy is based on cognitive radios that can detect the usage of spectrum resources in order to discover spectrum usage opportunities. White spaces can be determined by spectrum sensing [7][8], or – in case of rather static spectrum usage of the primary system – by means of geolocation combined with access to a spectrum usage database [9]. The interweave approach has typically been considered for secondary spectrum usage within the TV spectrum and has been endorsed by a recent ruling of the US Federal Communications Commission [9]. In the *overlay* operation the secondary system is assumed to be cognitive in the sense that it knows in advance the message that is transmitted by the primary transmitter, as well as the codebook of the primary system. This allows the secondary system to design its own transmitted signal such that interference from the primary system to the secondary receiver can be mitigated. At the same time, the secondary system can *cooperate* with the primary system by relaying the primary signal; this enables the secondary system to compensate for interference that it causes to the primary receivers. The overlay spectrum sharing has so far only been investigated from a theoretical perspective. In this paper, we apply the overlay approach to enable spectrum sharing between a primary TV broadcast system and a secondary cellular mobile broadband system. Furthermore, we quantify the feasibility of overlay-based spectrum sharing for both the TV and the cellular communication system. We show the performance gains of the proposed overlay approach for both the downlink and uplink of the cellular system. There are several reasons for targeting the TV spectrum for secondary usage. First, most of the TV spectrum is located in the lower UHF band around 470–700 MHz, which has favorable propagation properties for long-range wireless communications. Second, there is a large amount of spectrum allocated to TV broadcast systems (on the order of 300–400 MHz) so secondary usage of this spectrum can provide significant additional capacity. Finally, TV broadcast systems are comparatively simple due to their rather static network design, open standards and the public availability of information associated with TV transmitters.

This paper is structured as follows. In Section II we review the prior work on an overlay cognitive radio channel and describe the system model. In Section III we present the system architecture. We explain the transmission scheme in Section IV. Numerical results are shown in Section V, and their

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implication for network operators are discussed in Section VI. Section VII concludes the paper.

II. THE COGNITIVE RADIO CHANNEL

A. Prior Work

In the interweave approach, cognitive radios use their capabilities solely for dynamic access to unused frequency bands. To operate a network close to its capacity limits, this approach is too restrictive. Instead, the overlay approach relaxes the assumption of orthogonal transmissions, and attempts to exploit cognition more generally for cooperation, precoding against interference and interference cancellation. For the cognitive radio, these approaches were proposed and analyzed for the channel shown in Fig. 1, referred to as the *cognitive radio channel* [10]. This channel model captures the communication between a single primary and secondary communication pair. Cognition is modeled by assuming that the cognitive encoder knows the codebook and the data to be sent from the primary sender. The achievable rates for this channel were presented in [10][11]. The capacity in strong interference was determined in [12]. The capacity region for the Gaussian channel in weak interference was determined in [13] and [14] and extended to MIMO cognitive radio networks in [15]. The general rate region was later obtained in [16] and [17]. In this paper, we apply theoretical results and insights obtained in previous works to a realistic scenario in which the primary system is a TV network, and the cognitive system is a cellular network. As the TV network is a broadcast system, the considered scenario will extend the cognitive radio channel model in order to consider multiple non-cognitive receivers.

B. System Model

The cognitive radio channel model assumes overlay transmission in which the secondary system is allowed to share the bandwidth with the primary system. We consider the Gaussian cognitive radio channel. The input-output relationship is then given by:

$$\begin{aligned} Y_p &= h_p X_p + h_{sp} X_s + Z_p \\ Y_s &= h_{ps} X_p + h_s X_s + Z_s \end{aligned} \quad (1)$$

where X_p and X_s denote respective channel inputs (code-symbols) at the primary and secondary transmitters, and Y_p, Y_s denote corresponding channel outputs. Complex channel gains are denoted as h_p, h_{sp}, h_{ps} and h_s. Receiver noise Z_p, Z_s is zero-mean complex Gaussian with independent real and imaginary parts and variance N_i for $i \in \{p,s\}$. Power constraints at transmitters are:

$$E[|X_i|^2] \le P_i \quad \text{for } i \in \{p,s\}.$$

Due to cognition, the secondary encoder knows the data to be sent by the primary user, and hence it can encode (i.e., generate X_s) using both its own and the primary user's data.

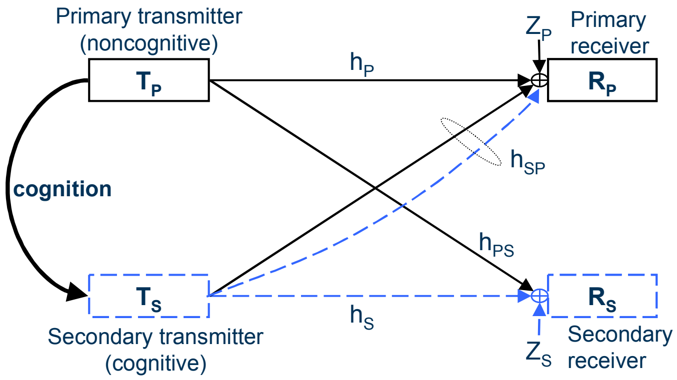

Figure 1. Cognitive radio channel.

C. Channel State Information.

In the system model considered in prior works, it is assumed that encoders have perfect knowledge of all channel gains in the system. In the scenarios considered in this paper, such knowledge is typically not available. Accordingly, we assume that transmitters do not have the knowledge of the exact channel phase (delay) to all primary TV receivers in the channel. We further assume that the path losses $|h_s|$, $|h_{ps}|$ and $|h_{sp}|$ can be obtained at the secondary encoder. How these channel gains are obtained will be explained in Section IV.

III. SYSTEM ARCHITECTURE

We consider the following scenario (see Fig. 2): a TV broadcast network is a primary user in its allocated frequency band. Similarly, a mobile cellular network operates in its allocated frequency band. In addition, the cellular network utilizes the TV frequency band as a secondary user in order to increase its capacity. Specifically, we will apply the cognitive overlay approach such that the secondary usage of the TV spectrum by the cellular system can occur within the service area of a TV transmitter.

There are some differences between the cellular and the TV system that are important for our proposed solution. A TV transmitter typically transmits at high power with up to several hundred kilowatts; this results in radio cell radii – or service areas – reaching beyond 100 km. In contrast, cellular networks have typical transmit powers around 20 W with cell radii of a few kilometers. This difference in scale between the TV and cellular systems allows us to derive different regions of secondary spectrum usage in the TV service area. Furthermore, TV systems are unidirectional, broadcast systems with one TV transmitter and multiple TV receivers for the same data stream. These properties require modifications to the original cognitive transmission schemes of a secondary system. A cellular radio cell has multiple users with mostly individual unicast data streams. Different data streams are separately transmitted by orthogonal signaling, e.g. by time, frequency and/or code division multiple access. Due to this orthogonality the cognitive transmission scheme for spectrum sharing can be applied to each of the cellular data streams independently. Traffic streams can be directed in either the downlink (from the base station to the user) or uplink (from the user to the base station) direction. The cellular network might use the TV spectrum in different ways. In one option the cellular network would use the TV channel as an uplink-only or a downlink-only carrier. The TV channel could then complement other cellular carriers in use to increase the capacity in one direction. The system would preferable operate in *frequency division duplex* mode. This option would be some special form of carrier aggregation that is considered for advanced cellular broadband networks [18]. Another option is to use the TV channel for secondary transmission in *time division duplex* mode. In this case, the cellular network would alternate between uplink and downlink transmission in the TV band. We will evaluate the transmission scheme and the performance independently for downlink and uplink secondary transmission.

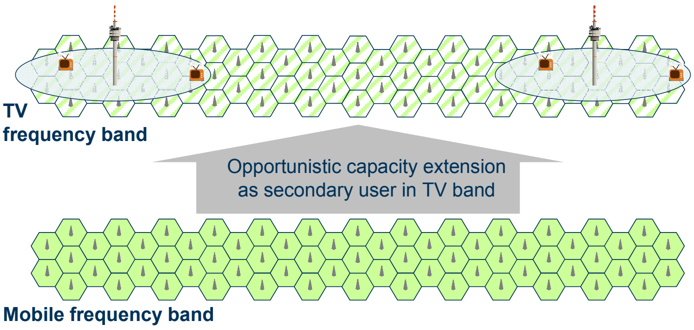

Figure 2. Usage scenario for secondary cognitive transmission.

In order to understand how a cellular network can adapt its transmission to a TV signal for cognitive transmission, we now present the system architecture of a digital TV (DTV) system, depicted in Fig. 3. The codewords are generated at a DTV encoder and are then distributed to the TV transmitters. Typically, TV radio networks are configured so that a specific radio frequency is only reused at large distances in order to avoid interference between neighboring TV senders. In between these areas the TV signal is transmitted on other TV channels. Most DTV standards also support a so-called *single frequency network* (SFN) operation. In this case, multiple transmitters with overlapping transmission ranges send the same signal on the same frequency at the same time. This effectively introduces multipath at the receiver. For example, the terrestrial video broadcasting (DVB-T) standard, which is based on coded OFDM, uses a guard period between transmission symbols. If multiple transmitters send identical data and the different signals are received within the guard period, the inter-symbol interference is fully compensated by the OFDM and the DTV receiver receives a stronger input signal [19][20]. SFN operation requires time-synchronized transmission from multiple senders. This synchronization can be achieved, e.g. with a common reference signal from the global positioning system (GPS). SFN operation provides higher spectral efficiency for DTV transmission at the cost of synchronous operation of the transmitters. It is also possible to use only local SFN operation. This is as indicated on the left hand side of Fig. 3, where only some neighboring DTV transmitters perform SFN operation in a local area.

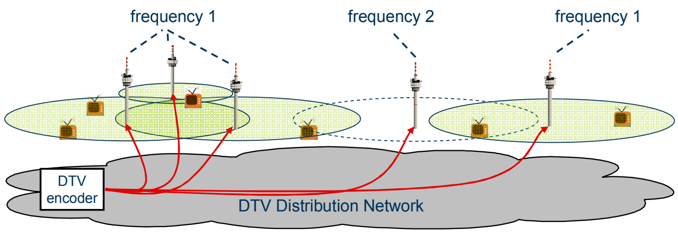

Figure 3. Architecture of a digital TV system.

An overlay cognitive secondary system needs to learn the codewords of the primary system and their transmission timing before they are transmitted. To enable that, we propose to connect the secondary cellular network to the primary DTV network as depicted in Fig. 4. We introduce a new TV band transmission management function in the cellular network, which can receive the DTV encoded primary codewords with their respective transmission timing. The TV band transmission management function determines which cellular cells shall be used for secondary transmission; this decision can be based e.g. on the load in the radio cells and the demand for additional capacity. The primary codewords and transmission timing are provided to those base stations via the cellular core network in the same way as they are provided to the TV transmitters via the DTV distribution network. As will be explained later in Section IV, cellular base stations (BS) can act as relays for the TV signal. It is important to note that this operation is easily based on the SFN operation of the broadcast system; the BSs essentially become local TV SFN transmitters. All the required distribution protocols and synchronization mechanisms are already in place.

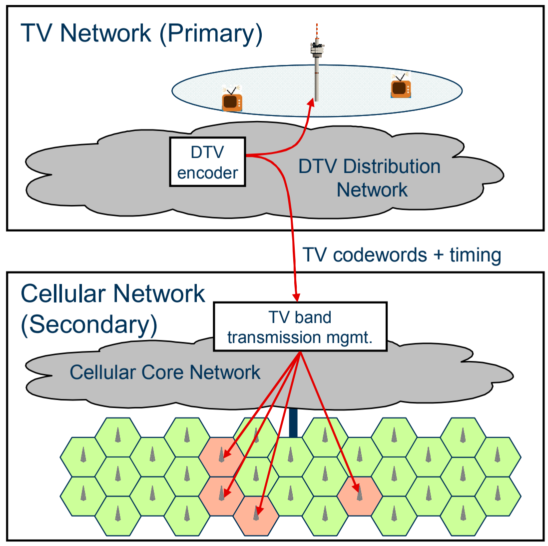

Figure 4. Coupled primary and secondary transmission networks (cellular radio cells with cognitive secondary transmission are marked in red).

In a TV system all users receive the same service, which is a TV data stream transmitted at a constant data rate. A receiver can successfully decode the TV signal if the signal-to-interference-and-noise-ratio (SINR) at the receiver is larger than a minimum SINR threshold γ_{TVmin}. The SINR value decreases with the distance between the receiver and the transmitter due to propagation path loss. Fig. 5 shows the SINR of an idealized TV signal over distance from the TV transmitter based on a simple propagation model. In this example a TV signal can be received up to a distance of approx. 227 km, which is the range of the TV service area. Primary-secondary spectrum sharing requires the secondary system to protect the primary service. For a TV system this means that the SINR of the TV signal needs to remain larger than the SINR threshold within the TV service area.

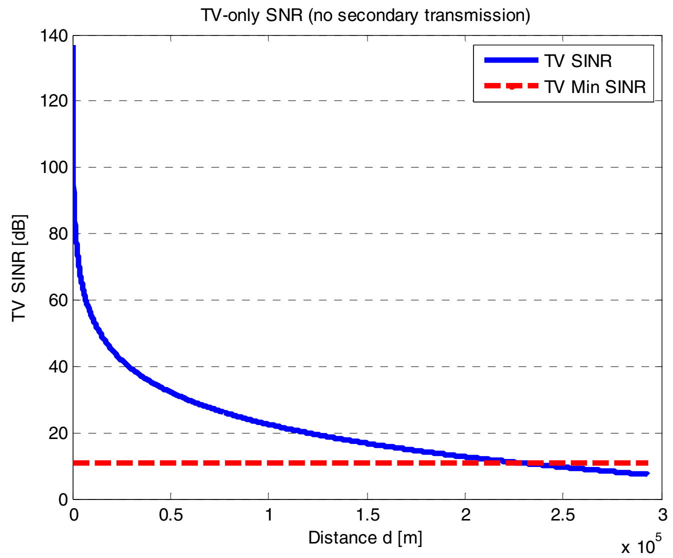

Figure 5. SINR of the TV signal over distance from the TV transmitter.

IV. TRANSMISSION SCHEME

A. *Secondary Downlink and Uplink Models*

We next describe the proposed encoding scheme. Transmission in the primary system is unchanged, as if the secondary system was not present. For the secondary encoder, we adapt elements of the scheme proposed in [14] as follows. The overlay cognitive system will introduce interference to the primary system when sharing the bandwidth with the primary system. To compensate for this interference, the cognitive secondary system will use (parts of) its transmission power to *cooperate* with the primary system. We distinguish between uplink and downlink transmission in the cellular system.

1) *Downlink*

The downlink channel model is depicted in Fig. 1. The cellular base station (BS) is the secondary transmitter (T_S) and the cellular user equipment (UE) is the secondary receiver (R_S). The BS learns about the TV transmission as described in Section III. The BS splits its power, P_{s_BS}, into two parts: with power $\alpha \cdot P_{s\_BS}$ it relays the primary signal, and with power $(1-\alpha) \cdot P_{s\_BS}$ it transmits secondary information to its desired user. Power $\alpha \cdot P_{s\_BS}$ will be chosen such that the quality of service (rate) at the primary receivers is unaffected by the presence of the cellular system. How this can be guaranteed for all TV users, and with imperfect channel knowledge at the secondary transmitter, will be explained in the Section IV.B. The two parts are encoded using superposition coding, yielding the channel input as:

$$X_s = \sqrt{(1-\alpha)} \cdot \hat{X}_s + \sqrt{\frac{\alpha \cdot P_{s\_BS}}{P_p}} \cdot X_p \qquad (2)$$

Codebooks are chosen to be Gaussian, i.e., $X_p \sim N[0,P_p]$, $X_s \sim N[0,P_{s\_BS}]$ and $\hat{X}_s \sim N[0,P_{s\_BS}]$. We consider two possible encoding/decoding schemes for the secondary communication:

1. $\hat{X}_s$ is generated via *dirty paper coding* (DPC) [21], while treating the signal carrying X_p as interference at the secondary receiver. This will remove the effect of interference at the secondary user, allowing it to achieve the rate as if this interference was not present.
2. No dirty paper coding is done at the cognitive encoder. Instead, the secondary receiver performs interference cancellation of the primary signal. Again, this will allow the cognitive receiver to achieve the interference-free rate.

We note that, unlike in the previous work, randomness in the phase precludes the possibility of coherent combining (beamforming) of primary information sent by two transmitters at a primary receiver. In fact, with this lack of phase information, the two codebooks used at the two transmitters should be independent in order to maximize the rate [22]. However, this encoding scheme requires modification of TV receivers – which is unrealistic in practice. Instead we require that the primary system remains oblivious to any secondary usage, which dictates that the secondary system uses the same codebook for primary information, as given by (2).

2) *Uplink*

The uplink transmission model is depicted in Fig. 6; it differs from the downlink in that the cognitive base station is now the receiver (R_{S_BS} in Fig. 6) and the user equipment is the secondary transmitter (T_{S_UE}). The UE is not aware of the primary transmission and the secondary channel input X_s encodes only the secondary message with a Gaussian codebook, i.e. $X_s \sim N[0,P_{s\_UE}]$, with the UE transmitter power P_{s_UE}. The UE causes interference to the primary TV receiver. The secondary system can compensate for this interference by relaying the primary signal from the cognitive base station. In contrast to the downlink case, the secondary transmitter that relays the primary signal (T_{S_BS}) is different from the secondary transmitter of the secondary communication (T_{S_UE}); we reflect this in our notation by adding BS and UE according to the indices of channel gains. Due to cognition, the BS can perform interference cancellation of the primary TV signal. We further assume that the base station receiver (R_{S_BS}) can be shielded from the base station transmitter (T_{S_BS}) so that the secondary received signal is not interfered with by the relayed primary signal. This enables the secondary communication link to achieve the interference-free rate.

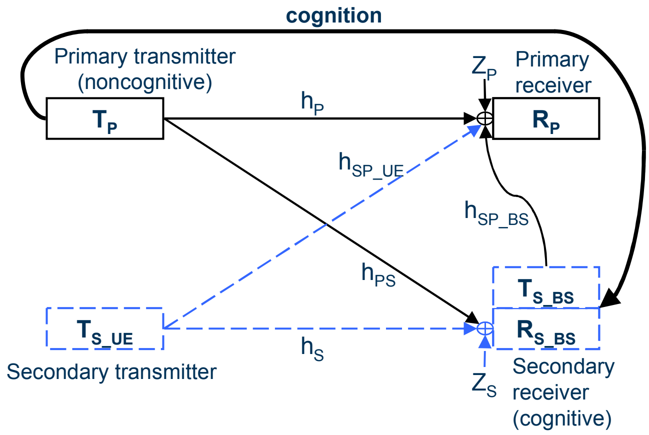

Figure 6. Channel model for the cognitive cellular uplink.

B. Protection of Primary Transmission By Relaying

1) Downlink

For the encoding scheme given by (2), the received signals (1) become

$$\begin{aligned} Y_p &= \left(h_p + h_{sp\_BS} \sqrt{\frac{\alpha \cdot P_{s\_BS}}{P_p}} \right) X_p + h_{sp\_BS} \sqrt{(1-\alpha)} \hat{X}_s + Z_p \\ Y_s &= \left(h_{ps} + h_s \sqrt{\frac{\alpha \cdot P_{s\_BS}}{P_p}} \right) X_p + h_s \sqrt{(1-\alpha)} \hat{X}_s + Z_s . \end{aligned} \quad (3)$$

From (3) it follows that the received SINR at the primary receiver is

$$SINR_p = \frac{\left| h_p \sqrt{P_p} + h_{sp\_BS} \sqrt{\alpha \cdot P_{s\_BS}} \right|^2}{N_p + (1-\alpha) \left| h_{sp\_BS} \right|^2 P_{s\_BS}} . \quad (4)$$

This SINR can be maximized by coherently aligning (i.e. beamforming) the received signals from the primary and secondary transmitters. We note that even if the phase was precisely known to the secondary transmitter (which we do not assume), the beamforming could only be done with respect to one single TV receiver. Instead, we assume that the phase difference between the two paths is random and uniform. The average SINR then becomes

$$\overline{SINR}_p = \frac{\left| h_p \right|^2 P_p + \alpha \left| h_{sp\_BS} \right|^2 P_{s\_BS}}{N_p + (1-\alpha) \left| h_{sp\_BS} \right|^2 P_{s\_BS}} . \quad (5)$$

In order to protect the primary system from service degradation, it is required to maintain an SINR at the receiver that is larger than the SINR threshold γ_{TVmin}. From (5) the power with which the secondary BS has to relay the primary TV signal in order to meet the TV protection requirement can be determined as:

$$\alpha = \frac{\gamma_{TVmin} \cdot \left(N_p + P_{s\_BS} \cdot \left| h_{sp\_BS} \right|^2 \right) - P_p \cdot \left| h_p \right|^2}{\left(1 + \gamma_{TVmin} \right) \cdot P_{s\_BS} \cdot \left| h_{sp\_BS} \right|^2}, 0 \le \alpha \le 1. \quad (6)$$

2) Uplink

Similarly to the downlink, the received signals in the uplink direction are

$$\begin{aligned} Y_p &= \left(h_p + h_{sp\_BS} \sqrt{\frac{\alpha \cdot P_{s\_BS}}{P_p}} \right) X_p + h_{sp\_UE} X_s + Z_p \\ Y_s &= h_{ps} X_p + h_s X_s + Z_s . \end{aligned}$$

The received SINR at the primary receiver is then

$$SINR_p = \frac{\left| h_p \sqrt{P_p} + h_{sp\_BS} \sqrt{\alpha \cdot P_{s\_BS}} \right|^2}{N_p + \left| h_{sp\_UE} \right|^2 P_{s\_UE}} .$$

The average SINR is

$$\overline{SINR}_p = \frac{\left| h_p \right|^2 P_p + \alpha \left| h_{sp\_BS} \right|^2 P_{s\_BS}}{N_p + \left| h_{sp\_BS} \right|^2 P_{s\_UE}} .$$

The power fraction required for cooperation becomes

$$\alpha = \frac{\gamma_{TVmin} \cdot \left(N_p + P_{s\_UE} \cdot \left| h_{sp\_UE} \right|^2 \right) - P_p \cdot \left| h_p \right|^2}{P_{s\_BS} \cdot \left| h_{sp\_BS} \right|^2}, \; 0 \le \alpha \le 1. \quad (7)$$

C. Secondary Communication Performance

1) Downlink

DPC or interference cancellation eliminates the effect of interference at the cognitive receiver. The obtained SINR at the cognitive receiver is then:

$$SINR_s = \frac{(1-\alpha) \left| h_s \right|^2 P_{s\_BS}}{N_s} .$$

In the case in which no DPC or interference cancellation can be performed, the secondary user will decode desired information while treating interference as noise, yielding:

$$SINR_s = \frac{(1-\alpha) \left| h_s \right|^2 P_{s\_BS}}{N_s + \left| h_{ps} \right|^2 P_p + \left| h_s \right|^2 \alpha \cdot P_{s\_BS}} .$$

2) Uplink

The obtained SINR at the cognitive receiver is

$$SINR_s = \frac{|h_s|^2 P_{s\_UE}}{N_s}.$$

For the uplink, we assume that the cellular base station will always be able to cancel the primary TV signal, since it already knows the TV signal by cognition.

D. Obtaining Channel State Information.

1) Downlink

In a cellular system, the channel gains are typically measured by the mobile receiver and then fed back to the base station. Hence, the secondary encoder can obtain the path loss value $|h_s|$. We also assume that the mobile receiver estimates the channel from the TV transmitter, and sends $|h_{ps}|$ back to the base station. This channel estimation can be performed if the pilot signal from the primary transmission can be decoded, i.e. if

$$INR_s = \frac{K_p |h_{ps}|^2 P_p + K_s |h_s|^2 \alpha P_s}{N_s + (1-\alpha)|h_s|^2 \alpha P_s} \geq \gamma_{TVpilot} \quad (8)$$

where INR_S is the interference-to-noise ratio at the secondary receiver and $\gamma_{TVpilot}$ is the required SINR for decoding the pilot signal. K_p and K_s are amplifications of pilot power at the primary and the secondary transmitters respective; boosting of pilot power is supported in some digital TV standards like DVB-T [20].

On the other hand, a TV receiver does not provide any feedback. The TV system has to guarantee that the threshold γ_{TVmin} is (probabilistically) met at every TV receiver within the TV service area (see Fig. 5). Consequently, the secondary system, in order to co-exist in the same spectrum, needs to choose the relaying power $\alpha \cdot P_s$ so that the required threshold is maintained at *every* TV receiver.

The locations of TV transmitters and their transmit powers are typically publicly available information and is assumed to be known to the secondary system. However, primary channel gains to TV receivers are not known to the cognitive encoder. Our solution to the problem is to define a *critical* primary TV receiver, as a hypothetical TV receiver which is the most severely affected by the secondary transmission. If the relay power is chosen according to the critical TV receiver, then all TV receivers are expected to receive at least the same performance as the critical TV receiver. The critical TV receiver is the one for which the SINR in (5) is the lowest when the relay power α is zero. Fig. 7 depicts two different TV receivers. Since the size of the radio cell is much smaller than the radio cell of the TV system $|h_p|$ is approximately the same for different TV receivers. The difference in SINR for different TV receivers is thus dominated by the interference caused by the secondary transmission. A realistic choice of a critical primary (TV) receiver is to assume that it is located at a minimum distance from the secondary transmitter. The channel gain $|h_{sp}|$ thus becomes a constant that can be determined according to a propagation model or measurement. The base station can also estimate the primary channel gain $|h_p|$ to the critical TV receiver (which is assumed co-located with the BS) by decoding the pilot signal of the TV system. Alternatively, it could be derived from radio environment maps that have been proposed for cognitive radio systems in the TV band [23]. With the estimated $|h_p|$ and $|h_{sp}|$ for the critical receiver, the relay power can be determined according to (6); with the measured $|h_s|$ and $|h_{ps}|$ secondary transmission can be performed with either dirty paper coding or interference cancellation.

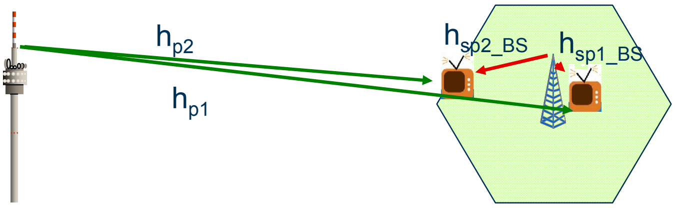

Figure 7. Estimation of channel state for critical primary receiver (downlink).

2) Uplink

For secondary uplink transmission channel estimation is performed similarly as for the downlink case; however, for the uplink more channels are involved as the cognitive relay (the BS) differs from the secondary transmitter (the UE) as shown in Fig. 8. With the same reasoning as for downlink transmission, the critical TV receiver in the uplink is the one which is separated by a minimum distance from the UE. The channel $|h_{sp\_UE}|$ is thus again a constant that can be determined by measurement or from a propagation model. In order to determine the relay power at the BS according to (7) the channel gains $|h_{sp\_BS}|$ and $|h_p|$ are required. Since the critical TV receiver is assumed to be located next to the UE, the BS can determine $|h_{sp\_BS}|$ to be similar to the BS-UE channel gain $|h_s|$. The primary channel gain $|h_p|$ can be estimated by the base station either from a radio propagation map or by measuring the TV channel gain and adding a location-specific compensation term from a propagation model. However, in contrast to the downlink case, in the uplink the critical TV receiver is not located next to the BS and may therefore perceive different shadowing (as indicated in Fig. 8); this can be compensated with a shadowing margin.

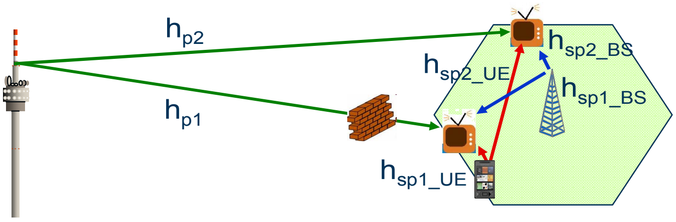

Figure 8. Estimation of channel state for critical primary receiver (uplink).

For the secondary transmission, $|h_{ps}|$ can be determined at the base station and used for interference cancellation. For this the condition (8) needs to be fulfilled. This is typically the case due to a higher channel gain of a BS compared to a TV receiver due to higher antenna height. The channel gain of the secondary radio link $|h_s|$ is derived from the secondary cellular signal sent by the UE.

V. Performance Evaluation

A. Simulation Setup

To demonstrate the performance gain of our proposed technique, we have evaluated a cellular overlay for a TV system via simulation. We consider only a single cellular radio cell and a single TV transmitter. The channel gains have been determined with the COST 231 Hata propagation model [24]

$$|h|^2 = \frac{1}{c \cdot r^e},$$

where r is the distance between the transmit and receive antennas and c and e are the propagation constant and the propagation exponent, respectively. The values of c and e for the different channels are provided in Table I. This propagation model allows simplifying the overlay system as the one-dimensional system depicted in Fig. 9, where channel gains only depend on the absolute distances between: the TV transmitter, the critical TV receiver, the cognitive base station and the user equipment. We denote as d the distance of the UE from the TV transmitter, and as displacement D the distance between the TV transmitter and the base station.

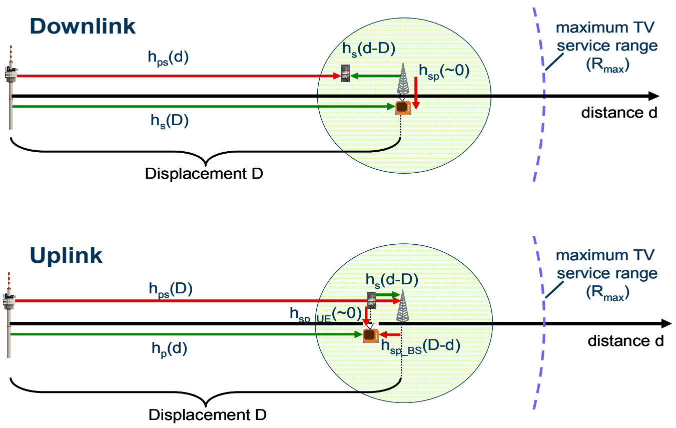

Figure 9. Simulation model within TV service area and $h(r)$ depending on distance r between transmitter and receiver.

If the secondary transmission takes place far away from the TV transmitter outside the TV service area we assume that the critical TV receiver – that needs to be protected – remains located at the service area edge. This case is depicted in Fig. 10 with the corresponding distances used to determine the channel gains.

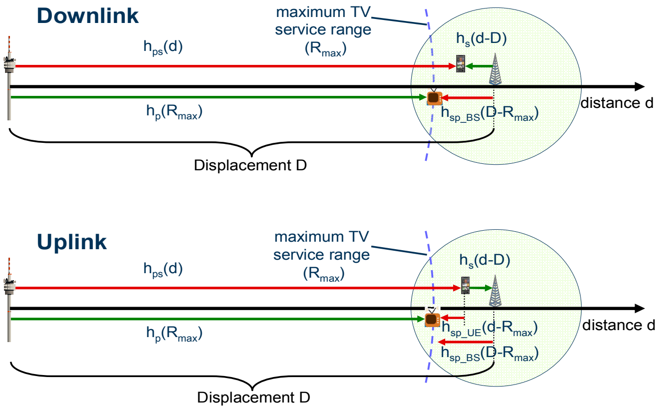

Figure 10. Simulation model outside TV service area.

The simulation parameters used in the numeric evaluation are listed in Table I.

TABLE I. System Parameters

Parameter		Value
Carrier frequency		500 MHz
Bandwidth (*B*)		8 MHz
Thermal Noise (N_p, N_p)		-135 dBW
TV transmit power (P_P)		50 kW
TV minimum SINR (γ_{TVmin})		10.9 dB [a]
TV minimum SINR for pilot ($\gamma_{TVpilot}$)		5.9 dB
Tolerable TV SNR loss at service area edge		0.1 dB
Cellular base station transmit power (P_{S_BS})		20 W
Cellular user equipment transmit power (P_{S_UE})		200 mW
Minimum distance BS➔TV receiver		30 m
Minimum distance UE➔TV receiver		10 m
Shadow margin for primary protection (uplink)		10 dB
Propagation parameters [b]: (constant *c*; exponent *e*) Path loss: $\|h\|^{-2} = c \cdot r^e$ with distance *r* between transmitter and receiver	h_p	(0.5; 3.2)
	h_{ps_UE}	(45.2; 3.2)
	h_{ps_BS}	($1.5 \cdot 10^{-5}$; 3.2)
	h_s	(25.5; 3.5)
	h_{sp_BS}	(0.3; 3.5)
	h_{sp_UE}	(13.5; 3.8)
Tolerable SNR loss at TV service area edge		0.1 dB

a. Corresponds to a Shannon capacity $B \cdot \log_2(1+SNR)$ of 30 Mb/s.

b. According to COST231 Hata model [24] assuming the following antenna heights: TV transmitter 80 m, TV receiver 10 m, cellular base station 30 m, cellular user equipment 1.5 m.

B. *Downlink performance*

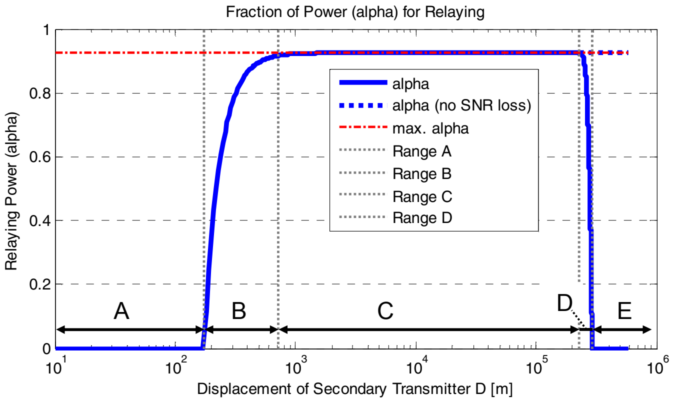

Figure 11. Required relay power vs. displacement of BS from TV transmitter.

The fraction of power (6) that is required for relaying the TV signal from the base station is depicted in Fig. 11, for different displacements of the base station from the TV transmitter. Five different regions can be distinguished. In *region A* (up to approximately 173 m) the relay power remains zero. In this region the signal power of the TV signal is so strong that even when a cellular base station is transmitting at full power, the received TV SINR remains above γ_{TVmin}. This can be seen in Fig. 12 and Fig. 13 where the signal levels and the SINR are depicted for a base station located at 86 m from the TV transmitter. Secondary transmission in region A is similar to the underlay approach of spectrum sharing: the secondary transmission exploits that it remains unnoticed by the primary system. (A difference is that it remains within a SINR bound of the primary system rather than below an absolute interference level as in [6].)

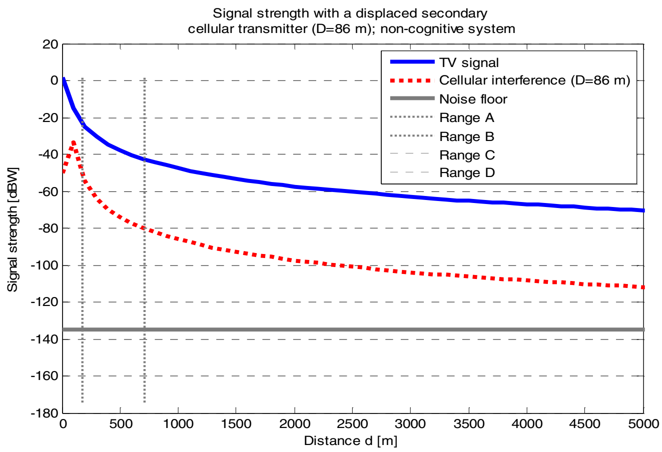

Figure 12. TV and cellular signal power over distance from TV transmitter with a BS displacement of 86 m.

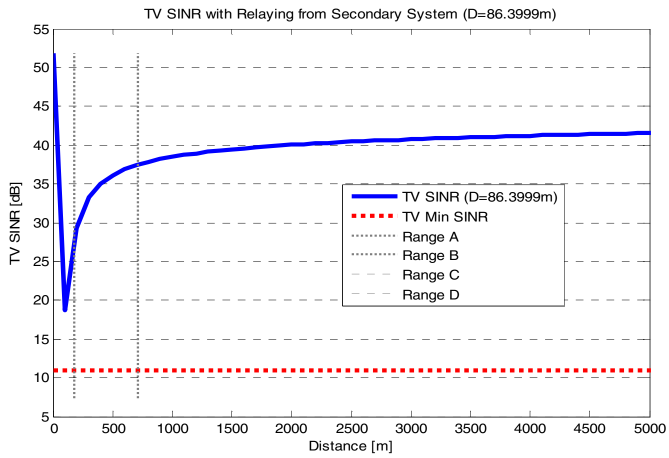

Figure 13. TV SINR over distance with a BS displacement of 86 m.

In *region B* of Fig. 11 the relay power starts to increase before it converges to a maximum value in *region C*; it covers the range of approx. 172–715 m displacement of the base station from the TV transmitter. The largest part of area is covered in region C, which comprises the displacement from 715 m up to the TV service area edge at 227 km. The relay power in region C is approximately constant at 93%; the maximum value of α can be determined as follows: with increasing distance of the base station from the TV transmitter the TV signal degrades. At sufficient separation the term $P_p{\cdot}|h_p|^2$ (and also N_p) becomes negligible in (5)–(6) compared to $P_{s\_BS}{\cdot}|h_{sp\_BS}|^2$, so the average SINR at the critical TV receiver reduces to

$$\overline{SINR}_p = \frac{\alpha}{1-\alpha},$$

which leads to a relay power of

$$\alpha_{max} = \frac{\gamma_{TVmin}}{1+\gamma_{TV\min}}.$$

This implies that in region C the TV signal transmitted from the TV transmitter becomes negligible at the critical TV receiver; only the base station remains significant, which transmits both the TV signal and the interference of the cellular signal.

Fig. 14 depicts the TV signal power over distance with a displaced base station relaying the TV signal with power fraction α according to (6). It can be seen in Fig. 15 that relaying ensures that the TV SINR never drops below γ_{TVmin}. Fig. 16 shows the same scenario but when the BS only transmits secondary information without relaying of the TV signal (i.e., α=0). In this case the TV service is disrupted in an area around the base station where the SINR drops below γ_{TVmin}.

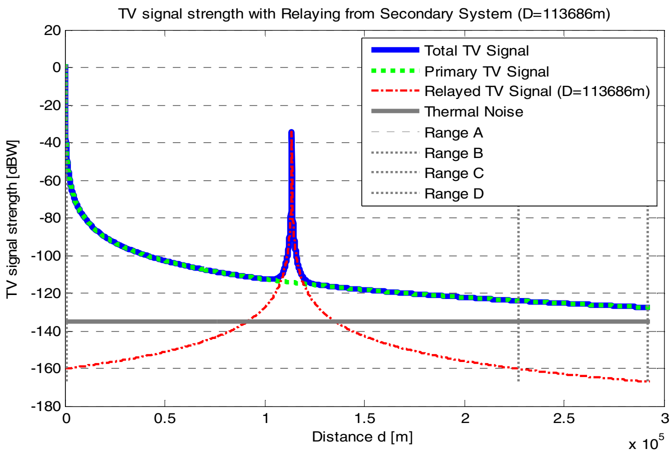

Figure 14. TV signal power over distance from TV transmitter with a cognitive relaying from a BS by ~113 km.

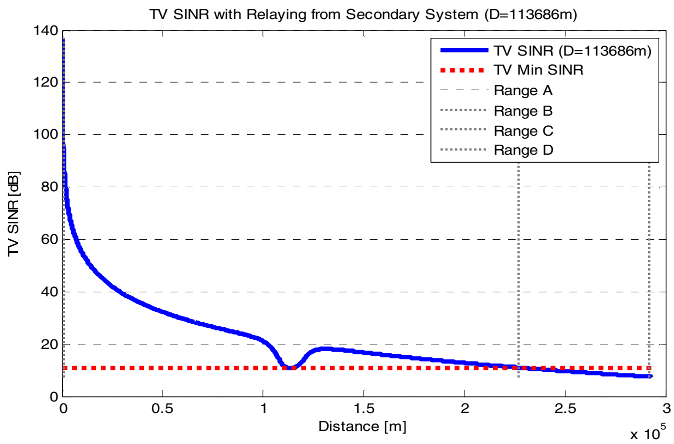

Figure 15. TV SINR over distance with a BS displacement of ~113 km and cognitive relaying from the BS.

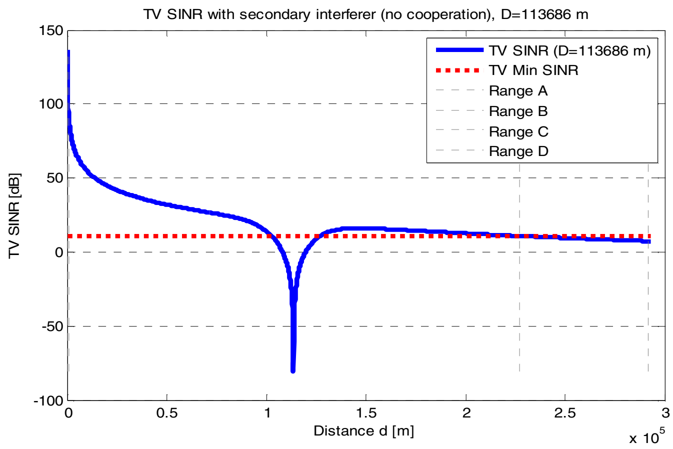

Figure 16. TV SINR over distance with a BS displacement of ~113 km and without cognitive relaying at the BS.

It is interesting to see from Fig. 11 that the relay power remains at α_{max} even outside the TV service area if no SNR loss for the TV signal is acceptable. This follows from (5): even a weak (i.e. very distant) interfering signal $|h_s|^2 \cdot P_s$ needs to be compensated with an equally weak relayed signal to maintain the SINR. If a small SNR loss (we assume 0.1 dB) at the TV service area edge is permissible, this results in a protection zone around the TV service area, as shown in Fig. 17 (this corresponds to *region D* with a displacement of 227–292 km in Fig. 11). In this area the relay power decreases with distance. Fig. 18 shows the TV signal levels for a cognitive BS operating in region D; by relaying with appropriate power the TV SINR is controlled to remain within the acceptable SNR loss at the TV service area edge.

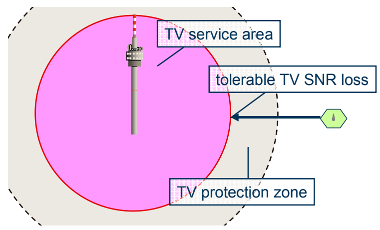

Figure 17. TV protection zone.

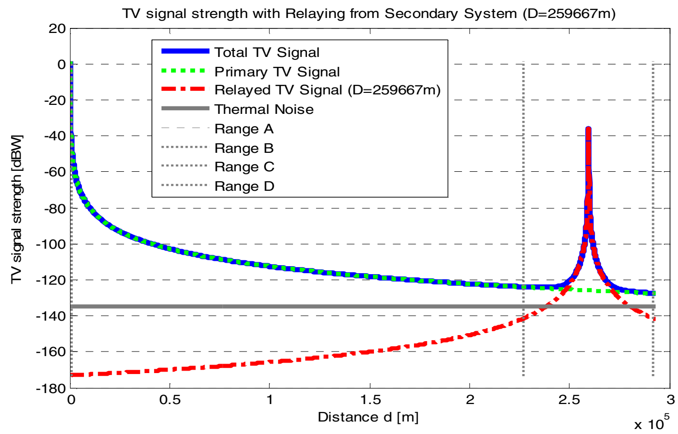

Figure 18. TV signal power over distance from TV transmitter with a cognitive relaying from a BS in region D.

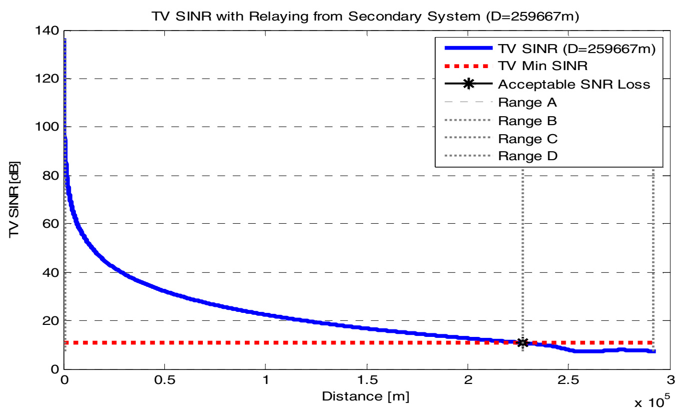

Figure 19. TV SINR with cognitive relaying from the BS in region D and an acceptable SNR loss at the TV service area edge.

In *region E* the secondary transmission is far away from the TV service area and secondary transmission does not interfere with the TV service. Transmission in region E with a

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protection zone (i.e. region D) corresponds to the interweave approach of spectrum sharing as investigated e.g. in [25][26].

Cognitive relaying of the primary system leads to a reduced capacity of the secondary system since only parts of the transmit power remains. This results in a loss of the link budget for secondary transmission as depicted in Fig. 20. In the dominating region C the loss is up to 11.5 dB. However, when comparing secondary cellular transmission in TV spectrum with a standalone cellular network transmitting around 2 GHz carrier frequency, the loss due to relaying is partly compensated by a path loss that is more than 10 dB lower at 500 MHz compared to 2 GHz.

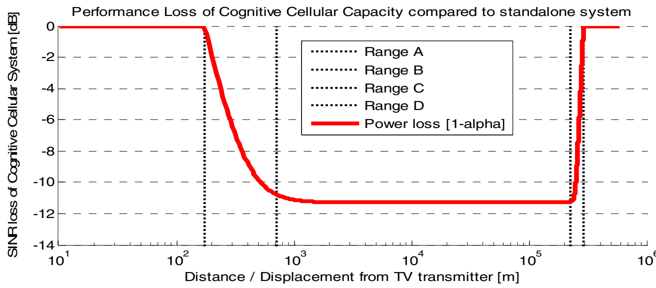

Figure 20. Performance loss of secondary downlink transmission.

C. Uplink performance

In uplink the power used for relaying the TV signal is only limited by the maximum transmit power of the BS. If we assume that no TV system is present, a UE with 200 mW transmit power could be separated from the BS by approximately 2 km and still obtain a data rate of 1 Mb/s according to Shannon capacity. When a TV system is present, the maximum distance between the UE and the BS depends on how far away the BS is capable of compensating for interference caused by UE transmission to a critical TV receiver. Fig. 21 shows that if a UE is located within ~429 m from the TV transmitter the BS does not need to relay the TV signal. If the UE is further away the BS is quickly limited by its maximum transmit power in preventing TV service degradation. Fig. 22 shows that the maximum distance between UE and BS that still allows protecting the TV service quickly drops to approx. 65 m for UEs outside region A. The UE-BS distance of 65 m corresponds to the distance where the maximum relay power α=1 is reached when $P_p \cdot |h_p|^2$ and N_p are negligible in (7). Fig. 23 indicates that the maximum displacement of a BS from the TV transmitter is 563 m such that continuous coverage can be provided to a UE; the continuous coverage range reaches up to ~635 m from the TV transmitter. For any UE located further away from the TV transmitter, secondary transmission without TV service disruption can only be achieved if the UE is within approx. 65 m from the BS up to the service area edge at 227 km as depicted in Fig. 24.

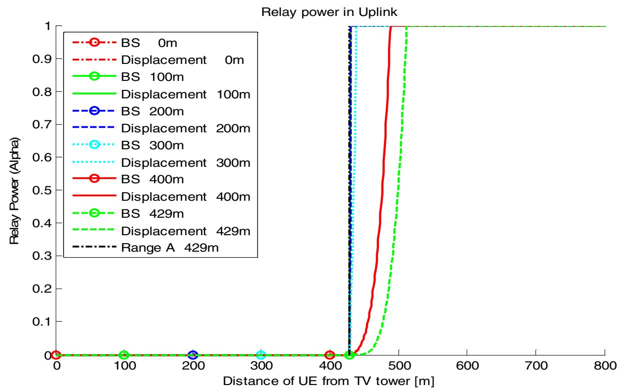

Figure 21. BS relay power vs. UE distance for different BS locations.

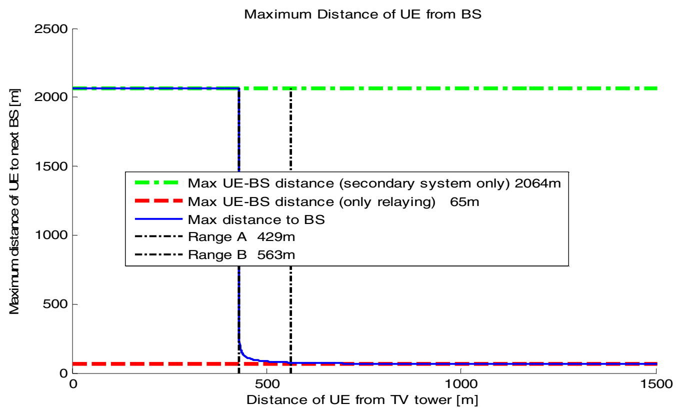

Figure 22. Maximum distance between UE and BS.

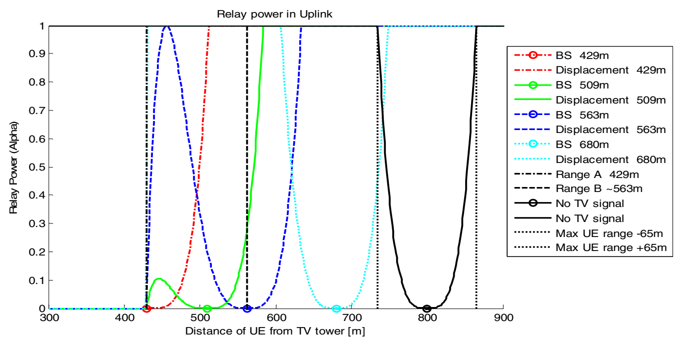

Figure 23. BS relay power vs. UE distance for different BS locations.

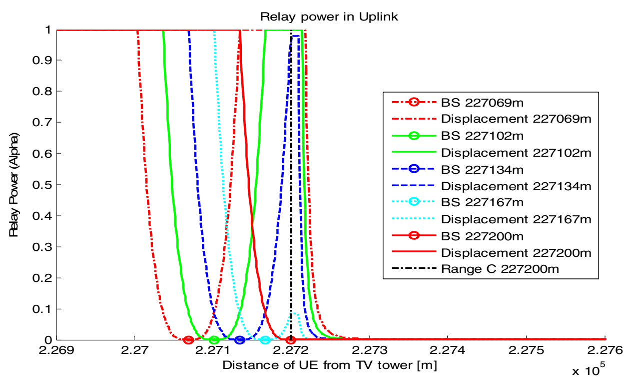

Figure 24. BS relay power vs. UE distance for different BS locations.

The performance degradation for uplink transmission of the secondary cellular network can be described as a loss of useful transmission range compared to a standalone cellular system. As shown in Fig. 25 there is no loss in cellular transmission range when the UE is located either very close to the TV transmitter (up to ~529 m) or if it is far away outside the TV service area and TV protection zone (around ~229 km). In the largest part of the TV service area the cellular transmission range is reduced to 3%.

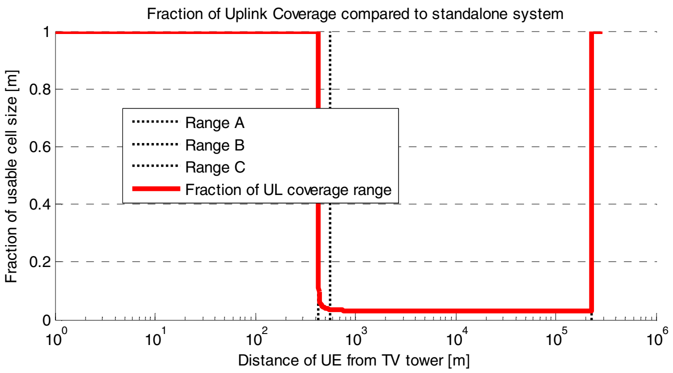

Figure 25. Performance loss of secondary uplink transmission.

VI. Discussion

The system architecture we present is based on a business model of a strategic partnership between the TV broadcast operator (with primary spectrum usage rights) and the cellular network operator. It assumes that the cellular network is the only secondary user that shares spectrum resources with the primary user. Secondary spectrum usage always has the drawback for a secondary operator that there is uncertainty about the availability of resources. This is a hurdle for any investment in network infrastructure dedicated to secondary usage, since a return on investment remains uncertain. In our system architecture only limited investment is required for the cellular operator. We assume that the operator already has a network infrastructure in place for cellular operation on a frequency band that is dedicated to mobile communication (see Fig. 2). Therefore, the secondary cognitive transmission only requires that a) the cellular base station (BS) and cellular user equipments (UE) support secondary cognitive transmission, b) the core network and transport network have sufficient capacity for DTV data stream distribution, c) a management system for secondary TV band transmission (see Fig. 4) is introduced, and d) that an agreement between the primary and secondary operators is obtained. Cellular networks are increasingly designed to be flexible in the spectrum bandwidth and frequency band they can operate in, and they can support time and frequency division duplex modes [18][27]. Therefore for requirement a) it seems to be a manageable effort to add a cognitive transmission mode. Also the addition of a corresponding management system for cognitive transmission (requirement c) should not be a significant obstacle. Novel cellular networks are further designed for mobile broadband services with cell capacities approaching aggregate data rates on the order of gigabit per second [18][27]. Therefore, high capacity backbone networks are used; this makes it possible to support additional DTV data stream distribution according to requirement b). The efficiency of agreeing on spectrum sharing contracts and the associated configuration of the network for cognitive transmission depends on the dynamics of these agreements (some form of secondary spectrum license). In theory, such agreements could have short time validity. However, given the static characteristics of TV networks and the complexity of the configuration of the cellular network for secondary transmission, it is likely that such contracts would be for time periods of weeks, months, or years. The secondary licensing process could be automated, e.g. by some form of regular auction. Different cellular operators could then determine their bidding price according to their traffic demand and need for additional capacity, as well as the market price for secondary spectrum licenses. The cellular operator could profit from this approach of secondary cognitive transmission by having potentially cheap access to additional spectrum capacity (at times when no additional spectrum is available for primary licensing), but also by being able to adapt the capacity that is provisioned in the network more dynamically to traffic demand (instead of buying a primary license over multiple decades based on vague long-term market predictions). For a TV broadcast operator cognitive transmission can also bear some advantages. In particular, secondary licensing for cognitive transmission can bring a financial gain. In addition, it can help in network planning and operation. A TV network has very large service areas; environmental structures can lead to certain regions with insufficient service performance. A TV network can compensate for this by adding gap fillers (e.g. co-channel repeaters), thereby creating local SFN regions. However, this requires deployment of costly infrastructure. At the same time, cellular network operators already provide a dense infrastructure – with more or less contiguous coverage – and the corresponding backbone network. Closing TV coverage gaps by cooperation with a cellular network can prove to be a more cost-efficient solution, as well as finer in granularity, compared to a stand-alone TV gap filling solution. Such a TV coverage obligation can be included in a secondary license agreement. To sum up: secondary cognitive transmission can provide benefits for both the TV and the cellular network operators.

VII. Conclusion

We have shown the feasibility of an overlay cognitive system in which the secondary user is a cellular network co-existent with a TV system in the same frequency band. To compensate for interference that it introduces, the cognitive encoder (base station) cooperates with the TV system, i.e. forwards the TV signal to TV receivers. Furthermore, it uses sophisticated encoding/decoding techniques to improve its own performance. Our approach, based on previously developed theoretical results, exploits characteristics of TV and cellular architectures to enable cognition in a primary network with multiple primary receivers. The presented solution allows a cellular network to coexist with the TV network without any modification to TV receivers. Different regimes of operation are observed depending on the relative positions of the two systems: 1) Low *interference regime*: in this regime no cooperation is needed. The required quality-of-service (SINR) at all TV receivers is met even in the presence of the interference. 2) *Moderate interference regime:* in this regime cooperation is done in order for TV receivers to meet the quality-of-service requirement. 3) *High interference regime* in this regime most of the base station power is used for cooperation.

Although the overlay architecture in general requires the cellular network to use part of its power to compensate for caused interference, it can still be a desirable mode of operation for cellular operators. The overlay approach allows an access to frequency bands that otherwise cannot be used. Furthermore, the current frequency allocation for TV systems has more favorable propagation characteristics than the cellular bands. This can lead, not only to increased rate performance, but also to better coverage in a cell.

Our results are optimistic showing the feasibility of the overlay paradigm and higher efficiency of bandwidth use. This is in particular the case for secondary cellular downlink transmission. For cellular uplink transmission the transmission range (and coverage) is strongly reduced due to power limitations at the BS, because of which the BS is only to a limited extent capable of ensuring the service quality of the primary system by relaying. In the future work, we plan to evaluate more general channel models and investigate the performance with more sophisticated propagation models. We also want to investigate the impact of imperfect dirty paper coding and interference cancellation.

Acknowledgment

The work of J. Sachs was supported by a grant of the Magnus Wallenberg Foundation for Scientific Research. Work by I. Marić and A. Goldsmith was supported in part from the DARPA ITMANET program under grant 1105741-1-TFIND, and the ARO under MURI award W911NF-05-1-0246.

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