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Spectrum Load Smoothing in IEEE 802.16 Systems

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Abstract Today's framework for radio spectrum regulation and spectrum usage is undergoing fundamental changes. In the face of scarce radio resources, regulators, industry, and the research community are initiating promising approaches towards a more flexible spectrum usage, as for example cognitive radios for dynamic spectrum assignment. In this work an intelligent algorithms is presented which supports operation of IEEE 802.16 radio systems in a commonly used spectrum in a flexible manner. The concept namely Spectrum Load Smoothing (SLS) is a method for service- and technology-independent assignment of spectrum ranges under consideration of Quality of Service support. The concepts is based on the possibility to predict spectrum usage based on observations of past spectrum usage. We apply the SLS to a coordinated dynamic radio resource management problem.

Keywords: IEEE 802.16, WiMAX, radio resource management, flexible spectrum use

1 Introduction

In the face of scarce radio resources, regulators, industry, and the research community are initiating promising approaches towards a more flexible spectrum usage, as for example cognitive radios for dynamic spectrum assignment as proposed by IMT-Advanced system requirements. In this work, medium access control protocols for cognitive radios performing coordinated dynamic RRM are discussed. They identify free spectrum, coordinate its usage and release it again when this is required by the incumbent base stations. The application of "waterfilling," a known principle in information theory, in the time domain is in this work referred to as Spectrum Load Smoothing (SLS). The concept of SLS [1] and [3] applied to WLANs and WPANs is adapted to WMANs. It's realization in cognitive radio networks that are based on IEEE 802.16 is examined in this work. The objective of SLS is to enable the distributed Quality-of-Service (QoS) support in shared spectrum in an intelligent, cognitive, way. The ability of the SLS to support QoS in the presence of other, competing cognitive radios and the prevention of harmful interference is evaluated.
The rationale and algorithm of SLS is introduced in [1]. SLS with reservation is examined in [3] at the example of WiMedia WPANs autonomously coordinating their resource reservations. A machine-understandable specification of the SLS as a policy in the DARPA XG Policy Language [5] in the context of policy adaptive cognitive radios is given in [2] and [4]. The idea of SLS is derived from the principle of waterfilling from the field of multiuser information theory and communications engineering: In a multiple transmitter and receiver environment, waterfilling is used to solve a mutual information maximization problem based on the singular-value decomposition of a channel matrix [7]. In the context of cognitive radios, the iterative waterfilling is also identified by Haykin [6] as an alternative to a game theoretic interaction in a distributed transmit power control problem.

This work considers the transfer of the waterfilling from its application in information theory to the SLS as part of the medium access of spectrum sharing cognitive radios in the time and frequency domain.
Krämling [12] and Rapp [13] have specified methods similar to the SLS for coordinating shared spectrum usage on the basis of observing past MAC frames in *High PERformance Local Area Network 2* (H/2). *Time Division Multiplex* (TDM) channels that are formed by repeated TDM intervals over multiple MAC frames are analyzed by Krämling [12] for the channel assignment in H/2. The placement of silent (idle) periods within a H/2 MAC frame and its influence on the overall system performance is evaluated in [13].
The remainder of this paper is organized as follows: Section II introduces SLS applied to WiMAX systems, the impact on the frame structure and MAC protocol. Next, Section III describes the multi cellular simulation scenario and all related assumptions. In Section IV we present the results of our dynamic, event-driven, stochastic simulations focusing on the coordination of co-channel cells. Section V concludes the paper and gives an outlook on future work.

2 Spectrum Load Smoothing in WiMAX System

SLS is able to support coordinated dynamic RRM, which comprises the synchronization co-channel- as well as neighbour cells, allowing for temporarily and locally increased capacity of the network. First we present how to coordinate co-channel cells by means of SLS. Afterwards we outline how coordination of adjacent cells can be supported. Synchronized system is assumed in which all BSs start their frame transmission simultaneously. Propagation delay is assumed to be within the cyclic prefix and can thereby be neglected.

2.1 Coordination of Co-channel Cells

A system with a initially fixed frequency reuse pattern is assumed which is done during system setup. When co-channel cells are coordinated, a cell remains operating only on its dedicated channel but more intelligently.

The concept is explained in an example deployment of Figure 1, with Cluster Order (CO) three (with channels c_1, c_2, c_3). One centre cell is surrounded by six co-channel cells of the first tier (blue). White cells are assumed to operate on different frequency bands (c_2 and c_3) and their interference is ignored. Two different traffic load cases are distinguished: (i) the low load and (ii) the middle to heavy load situation.

2.1.1 Low Load (i)

Figure 2 shows SLS applied to a cellular deployment of Figure 1 in low load. The DL subframe is divided into time *slot a, slot b, slot c* and *slot d* which are dedicated for the corresponding cells c_1^a, c_1^b, c_1^c and c_1^d. For instance a cell of class c_1^a allocates all its transmissions within *slot a*, simultaneously with all other cells of sub-cluster c_1^a. As a result, the frequency reuse distance is doubled in low load. The number of slots is a parameter[1] which is evaluated in section IV.
The allocation of slots to cells can be found de-centrally by observation of the interference level. Optionally the slot pattern can also be centrally controlled by a management authority sending signalling messages over the wired backhaul. In this manner, transmissions of a system are distributed uniformly over the DL subframe. Interference between co-channel cells can be avoided, but in the broadcast phase, as long as transmissions of a cell fit in its own slot. If a slot is full and a BS can not allocate more transmissions within it, middle to heavy load case is reached.

[1] The seven cells are approximately uniformly assigned to *n* slots.The value *n* is set to 1, 2, 4 and 7 in the evaluation of section IV.

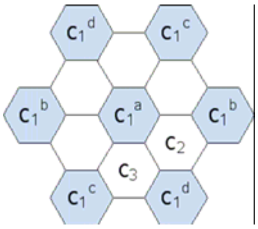

Figure 1. Cell cluster with CO 3 and sub-clustering 4

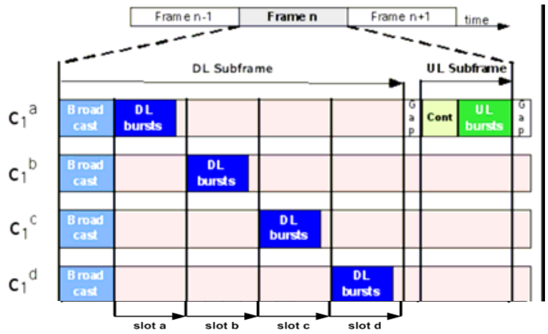

Figure 2. IEEE 802.16 Frame with time division multiplexed DL

2.1.2 Middle to Heavy Load (ii)

Figure 3 shows the previously presented SLS approach in middle to heavy load. If a single timeslot does not satisfy the resource demand of the cell, transmissions are scheduled in other time slots. Then a BS potentially allocates packets at the end of all other slots. It starts to take more time from other slots, from the end to the beginning, as its own load increases. By measuring the interference level a cell chooses the transmission opportunity with the lowest interference level which is closest to the end of a slot. In this manner the frame is uniformly utilized over time, i.e., spectrum load smoothing.

In middle to heavy load, co-channel cells transmit simultaneously and mutually interfere each other. The number of simultaneous transmission increases with increasing traffic. But SLS yields a constant interference level over the DL sub frame. For example before a third transmission in parallel occurs the whole frame has two parallel transmissions.

The medium is still used with different degrees of exclusiveness, especially in middle load. At the beginning of its own slot each cell has more exclusive access to the medium because other cells start its potential allocation at the end [Figure 3]. In this period of time low interference occurs and sensitive PHY modes can be used or low packet loss rate can be achieved. By employing this period for instance for time critical services, QoS is supported. As an optional feature the degree and duration of exclusiveness at the beginning of a slot can be an parameter which is subject to future studies.

The presented enhanced usage of resources require an extension of the protocol messages to indicate burst transmissions on different frequency bands to the SS and to indicate activity reports to the BS. Additionally mutli channel or multiband capable BS are required.

The partitioning is always applied but the effect is expected to gradually disappear with increasing traffic load. One cell without enough resources in its own partition allocates packets at the end of all other partitionings. And it starts to take more resources from other partitions from back to beginning as its own load increases. In middle load, the access is exclusive at the beginning of the own partitioning, whereas transmissions are already interfered at the end of the own partitioning. With increasing load the interfering transmissions are closer allocated to the beginning of the partitioning. In full load all cells occupy the whole frame independent of the partitioning order.

2.2 Coordination of Neighbor Cells

Besides the approach to divide resources into time slots for exclusive use of subclasses of cells, the SLS can be used to satisfy local fluctuations of capacity demand. If a single cell has an increased traffic up come, resources of direct neighbour cells are migrated to this heavily loaded cell. Figure 4 shows the enhanced frame structure of a heavily loaded cell. Free phases of the frequency bands of the direct neighbour cells are also used by heavily loaded cell. In order to avoid interference, only resources can be reused which are unused by all neighbour cells operating on a specific channel.

2.3 *Spectrum Access by Mutual Observation*

If cells are coordinated by mutual observation, transmission opportunities can be indentified by BS or SSs. Here exemplarily for the downlink, we propose to let the SSs acquire the needed information and let them send the spectrum usage pattern to the BS. This approach allows accounting for individual SINR situation of each SS in downlink and thereby for more efficient link adaptation.

Figure 5 shows an example receive power pattern, perceived by a single SS. The power peak of the frame header is depicted as well as a DL transmission to the observing SS. In a second step the SS transmits the measured power pattern to the BS.

Table I. Overhead rate of approach "observing SS"

	Quantization [bit]			
Sampl. Freq. [Hz]	1	2	3	4
100	100	200	300	400
200	200	400	600	800
400	400	800	1200	1600
800	800	1600	2400	3200
1600	1600	3200	4800	6400
3200	3200	6400	9600	12800
7200	7200	14400	21600	28800

Table II: resource consumption for an overhead rate of 28.8 kbit/s; Mean: 1.99 symbols per frame per user

Modulation and Coding Scheme	User percentage	Bits per symbol	Symbols per frame at 28.8 kbit/s
BPSK 1/2	39.4	96	3
QPSK 1/2	20.56	192	1.5
QPSK 3/4	27.95	288	1
16 QAM 1/2	4.1	384	0.75
16 QAM 3/4	5.15	576	0.5
64 QAM 2/3	0.92	768	0.375
64 QAM 3/4	1.92	864	0.33

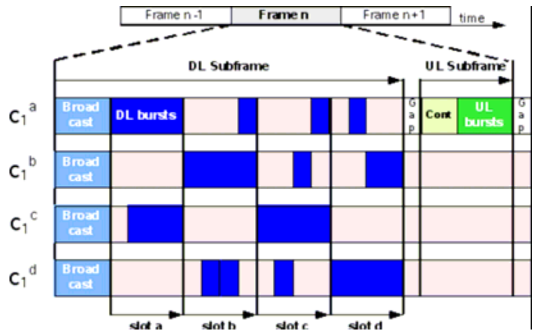

Figure 3 . IEEE 802.16 Frame with time division multiplexed DL bursts at middle load

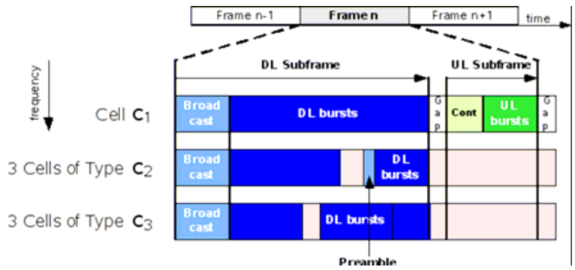

Figure 4 Clustering on FDM

The BS processes the pattern by subtracting its own transmissions pattern considering all transmissions to SSs of its cell. Figure 6 depicts the transmit pattern of the BS, indicating the frame header and three DL transmissions. Now the BS can generate a filtered power pattern for each SS, shown in Figure 7, by combining the patterns of Figure 5 and 6. With the filtered power pattern, the BS is able to identify transmission opportunities and exploit them by allocating new downlink transmissions to these unused resources.

The required signalling overhead (for sending the interference level perceived at the SS to the BS) depends on size of the transmission opportunities and the quantization of the measurement. Table I presents the resulting overhead rates of different sampling

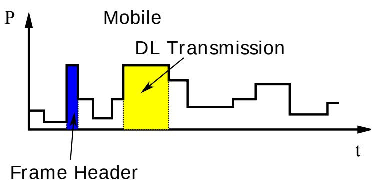

Figure 5. Perceived receive power at the SS

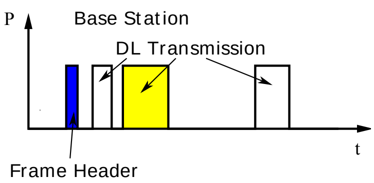

Figure 6. Transmit pattern of the BS

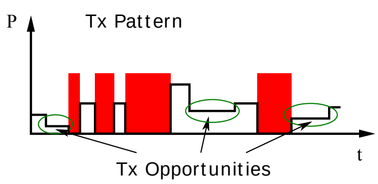

Figure 7. Filtered power pattern of the SS

frequencies (from 0.1 to 7.2 kHz) and types of quantization (from 1 to 4 bit). For example if a SS generates one sample per 10 OFDM symbols (i.e. 7.2 kHz sampling frequency with $T_{symbol} = 13.89 \times 10^{-6}$s) and uses a 4 bit quantization (allowing 16 different interference levels), it produces a signalling traffic of 28.8 kbit/s. This resource consumption can be further reduced by scanning on demand and using lower quantization. Only one bit per sample is required if a threshold is used at the SS for deciding whether a transmission opportunity is to be used or not.
For a signalling traffic of 28.8 kbit/s the resulting symbol occupation is given in a Table II. This Table bases on the switching points of the MCS in a free space propagation scenario with uniformly distributed SS in a cell [Fig. 8]. A SS at the cell edge using BPSK 1/2 occupies in average three symbols per frame whereas a SS close to the BS using 64 QAM 3/4) occupies in average one symbol every third frame.

3 Simulation Scenario

The evaluated scenario consists of 7 cells, each with a central BS and 25 SSs. The locations of the BS and the SS is shown in Fig. 9. Measurements are only performed in the central cell (black) for the corresponding BS and SSs. The stations in the surrounding 6 cells only produce interference and are not evaluated. Nevertheless, the same event driven stochastic simulation, with identical average traffic loads, and with the same degree of detail, is conducted at all 182 stations. The cells have a radius of R = 1750m and an N = 7 (or 3) cell CO is used as shown in Fig. 9. Cells that are not shown are assumed to operate on different frequency bands and their interference is neglected. The nearest interfering cells (red) have a distance of $D = \sqrt{3N}R = 8020m$. The “C1 LOS” pathloss model for a suburban environment [9] is used in the following. As the cells are synchronized, all base stations transmit their DL and UL MAPs at the same time. They have to use an omnidirectional broadcasting pattern which means that the users experience worst case SINR levels during these times.

3.1 Simulator and Traffic Model

The open Wireless Network Simulator (openWNS) developed at our department [10] is a time discrete, event driven simulator. The load generator of each station generates IP data packets according to a specified arrival process and feeds them into the WiMAX data link layer (DLL) via the suitable Service Access Point (SAP). When a packet is scheduled, it is forwarded to the physical layer (PHY) module that adds the packet’s transmission to the set of currently active transmissions in the scenario. Until the transmission is over, all other packets transmitted at the same time on the same frequency band experience the interference generated by the transmission, taking into account pathloss and antenna characteristics in form of the beam pattern. For all SSs we apply symmetric Poisson traffic in DL and UL direction. For each run, the following performance values are derived and

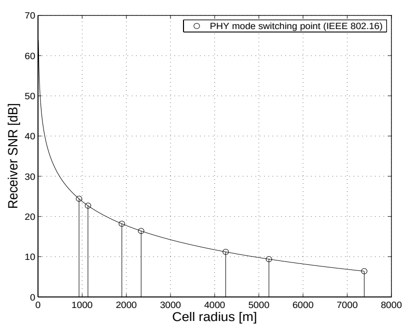

Figure 8. IEEE 802.16 OFDM switching points with free-space, 20 MHz bandwidth, single cell

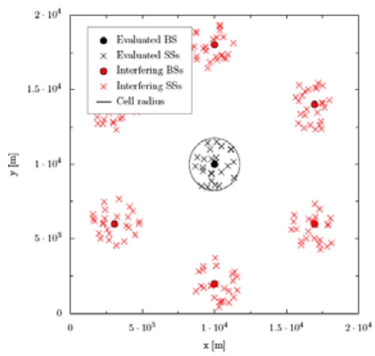

Figure 9. Positions stations in central (black) and co-channel (red) cells of evaluated clustered cellular deployment

evaluated:

Throughput: Measured in Bit/s as the total bits of all packets successfully arriving at the WiMAX SAP of the destination station during a fixed time window. Separate values are measured for UL and DL direction.

Packet Delay: Measured at the destination station's WiMAX SAP for all packets that have been successfully transmitted. Defined as the time elapsed between entering the sender's WiMAX protocol layer until leaving it at the destination's WiMAX SAP. In particular, all delays experienced in buffers are counted. It should be kept in mind that in overload conditions, the mean delay values are only partly meaningful. The reason is that the infinite delay of packets that are never transmitted is neither included in mean values nor counted because these packets never reach the destination's WiMAX SAP. The delay figures are always given in seconds.

Signal to Interference and Noise Ratio (SINR): Ratio calculated from the measured values at the receiver: transmission's carrier power and the sum of interference and noise, in [dB].

3.2 Link Adaptation and Error Modeling

The scheduling strategy performs link adaptation based on the SINR estimations, provided by the spatial grouper. For each packet that is scheduled for transmission to a subscriber station, a modulation and coding scheme (MCS) (also referred to as PHY-mode) with the respective PHY data rate is chosen according to the SINR threshold values shown in table III. The SINR threshold values aim at a target residual bit error rate (BER) of 10^{-6}.

3.3 WiMAX Frame Structure and Overhead

Broadcast messages such as MAPs are transmitted by an omnidirectional antenna pattern. Unidirectional DL and UL bursts are transmitted by beamforming for concurrent SDMA transmissions. The *optimal beam former* [12] is utilized for the SDMA mode. The BS can schedule multiple concurrent bursts and sets beam patterns accordingly to separate the co-scheduled users' signals. OFDM is used, i.e., the 192 data carriers available in the 20 MHz bandwidth are grouped into a single frequency channel. Each OFDM symbol is 13.89 10^{-6} seconds long, making for a total of 720 OFDM symbols in each 10 ms frame [8]. Each MAP is transmitted using BPSK 1/2 as the modulation and coding scheme. Using 192 data carriers, 96 bits can be transmitted with one symbol. Thus, an UL MAP holding 25 information elements is 14 full OFDM symbols long (1.94% of the frame). A DL MAP holding 75 information elements needs 39 symbols (5.4% of the frame). 7 OFDM symbols are deducted from the frame capacity to account for the different phases of the preamble. In total, the organizational overhead for the whole frame is 8.3%.

3.4 Other Simulation Parameters

The performance of the coordination scheme is evaluated without the effects of Segmentation and Reassembly (SAR) or Automatic Repeat Request (ARQ) mechanisms. Each base station is equipped

Table III: MCS Switching Threshold & PHY Data Rates [8]

#	Modulation	Code rate	Min. SINR [*dB*]	PHY data rate [*MBit/s*]
1	BPSK	1/2	6.4	6.91
2	QPSK	1/2	9.4	13.82
3	QPSK	3/4	11.2	20.74
4	16 QAM	1/2	16.4	27.65
5	16 QAM	3/4	18.2	41.47
6	64 QAM	2/3	22.7	55.30
7	64 QAM	3/4	24.4	62.21

Table IV: Overview Of Common Simulation Parameters

Parameter	Value
Cluster Order	Variable (3 and 7)
Cell radius	1750 m
Mobility	none
Height BS/MS	32 m / 1.5 m
Tx Power BS(per cell) / SS	30 dBm
Mid frequency	5.47 GHz (CEPT band B)
Pathloss	WINNER „LOS C1"
Shadowing & Fast Fading	No
Antenna array/elements	ULA / 9
Max. number of beams	4
Channel bandwidth	20 MHz
Traffic type	Symmetric Poisson
Packet size	1024 Bits (fixed)
MAC Frame length	10 ms (720 OFDM symbols)
Data subcarriers	192
OFDMA symbol duration	13.89 µs
SAR & ARQ	None
Scheduling strategy:	Proportional Fair

with a 9-element uniform circular antenna array. SSs are equipped with a single element omnidirectional antenna. The transmit power is fixed at 1 Watt for a BS and SS. A mid frequency of 5.47 GHz is used. All stations are assumed at a fixed position as depicted in Fig. 3. As a roof-top deployment is envisioned, the pathloss model presumes LOS conditions. The “LOS C1“ path loss model for the urban environment [9] is used in the following. Shadowing or fading effects are not considered. Table IV gives an overview of all relevant simulation parameters.

4 Simulation Results

In this section, we present and discuss the results of the performed simulations for coordination of co-channel cells by means of SLS. First, we discuss throughput, packet delay and SINR values for four different numbers of slots per frame: 1, 2, 4 and 7 (further referred as partitioning). Without loss of generality, only SLS techniques for DL traffic are shown.

Figure 10 shows the cell downlink throughput over the offered traffic for the CO three and seven. Additionally, the varying parameter is the type of partitioning, i.e., number of slots in the IEEE 802.16 frame according to Figure 2 and 3. As expected, the saturation throughput increases with higher CO. With CO three the saturation throughput is 10 Mbit/s whereas with CO seven it is 15 Mbit/s, independently of the frame partitioning. With higher CO the reuse distance increases and thereby the SINR values rise. Though, the spectral efficiency per area decreases by almost 35% from CO three to seven from 4.713 Mbit/Hz/m² to 3.030 Mbit/Hz/m². The order of the frame partitioning does almost not impact the saturation cell throughput. Independently of the partitioning order, in full load all cells occupy the whole frame. Nevertheless, with CO seven a minor increase of the saturation throughput can be obtained with rising partitioning order. The higher the order of partitioning, the higher SINR values are perceived from weak SSs at the beginning of each partitioning. System without frame partitioning are not able to serve associated SS at the cell edge with low SINR values.

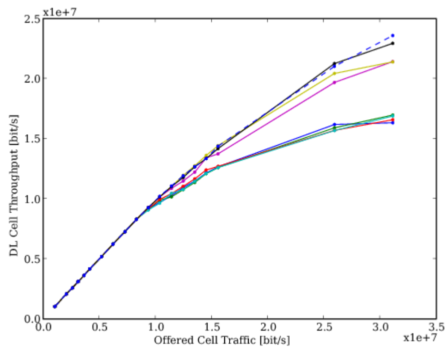

Figure 10. Downlink cell throughputs for several CO three and seven and for several frame partitioning schemes

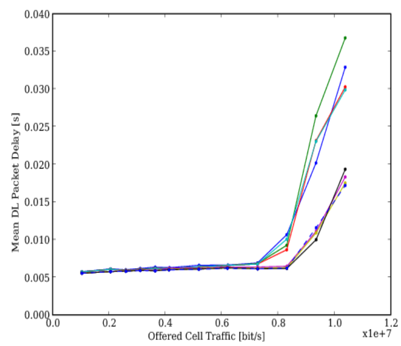

Figure 11. Downlink packet delay for CO three and seven with several frame portioning schemes

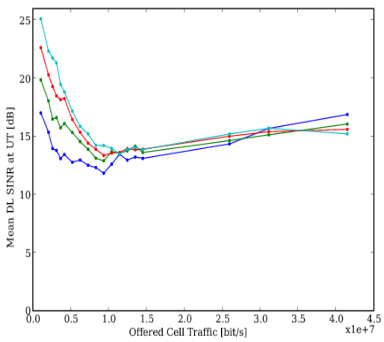

Figure 12. Mean DL Signal to interference level at receiving subscriber stations

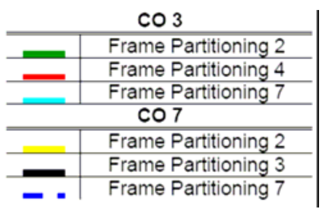

Figure 11 shows the DL packet delay over the offered traffic for CO three and seven. The DL packet delay remains at about 5 ms for all scenarios at a low load. The point of increasing DL packet delay is at an offered traffic of 7 Mbit/s with a CO three and at 8.2 Mbit/s with CO seven. Frame portioning can slightly decrease the mean DL packet delay, especially for CO three. The packet delay without partitioning is improved approximately by 2ms with two slots, by 3ms with four slots and only by 1ms with seven slots. The gain in packet delay by introducing slots can be explained by the increased SINR and MCS at the beginning of each slot. With CO seven the gain is reduced because the SINR becomes less predictable. A lower number of interferers causes a higher relative estimation error when one interferer joins or leaves a transmission opportunity.

Figure 12 shows the mean Signal to Interference plus Noise (SINR) level of DL packets for CO seven. In this case the frame partitioning gives a significant increase of the mean SINR level for low load situations. The gain in the mean SINRs is proportional to reduction of simultaneous transmitting cells at the beginning of a slot. The SINR gain compared to the reference case without partitioning (7 simultaneous cells), is 3dB for two slots (4 simultaneous cells and a ratio of 7/4), 6dB for four slots (with 2 simultaneous cells and a ratio of 7/2), and 8dB for seven slots (1 transmitting cell and a ratio of 7/1). The gain of SINR decreases with higher traffic load. When the offered traffic reaches the saturation throughput, the frame partitioning does not have any measurable benefit.

5 Conclusion

An intelligent algorithm is presented which supports operation of IEEE 802.16 radio systems in a commonly used spectrum in a flexible manner. The concept is based on the possibility to predict spectrum usage based on observations of past spectrum usage. We apply the SLS to a coordinated dynamic RRM problem in two different cases the coordination of co-channel- and neighbour cells. Medium access control protocols identify free spectrum, coordinate its usage and release it again when this is required by the incumbent BS. The simulation results for the coordination of co-channel cells show a significant increase in the mean SINR for the low load situation, of up to 8 dB. The achieved gain in SINR potentially allows further increasing the system performance by decreasing the interference level or reducing the transmission power by applying an adaptive power control. In this manner, in uplink the battery life of mobile terminals can be extended. Gain in SINR must compensate additional resource requirements of the coordination which's additional signalling overhead is evaluated and means are shown to reduce it significantly.

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