Analysis of a TDMA Coexistence Approach for IEEE 802.16 Systems

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***Abstract*—Today's radio frequency regulation is undergoing fundamental changes. There is a high demand for radio frequency spectrum for data communication but no blank spots in the frequency assignments plan. Under the approach of coexistence and cognitive radio multiple systems can share spectrum in unlicensed bands. Additionally non-exclusive licensing allowing secondary systems to occupy spectrum if the primary license holder is absent are emerging. In this case multiple systems can compete for spectrum access. In this paper we present an approach how two IEEE 802.16 systems can coexist in the same frequency band. The basic approach is to define rules how the systems can schedule their transmissions to provide spectrum opportunities for each other. The key idea is to have one system transmit at the beginning and the other at the end of each frame.**

Analytic and simulation results are presented showing how systems can estimate available capacity and the impact of their behaviour to own and overall performance.

I. Introduction

Radio frequency spectrum is the key resource required for wireless communication. All frequencies suitable for wireless communication are either exclusively assigned to license holders or dedicated to unlicensed operation. Often license holders, also referred to as primary users, do not occupy the spectrum they own. They either do not transmit at a given geographic location or not at a given time. These idle resources can be used by other, secondary systems. In this coexistence scenario with primary and secondary users the secondary system has to stop operation immediately when detecting a primary user. There can be multiple secondary systems operating in a band if the primary system is not present. In this case the systems have to follow defined rules to assure fair access to the medium. A common mechanism for that is Carrier Sensing (CS).

Coexistence of multiple wireless communication systems can help to increase resource usage and therefore increase spectral efficiency. Research directions are therefore manifold. Figure 1 gives an overview of possible scenarios aligned as a matrix. The dimensions shown are *heterogeneity* and *overlapping* meaning the following:

Heterogeneity: decides whether evaluated systems belong to one (homogeneous) or different technology standards (heterogeneous).

Overlapping: describes how much coverage area of one system is influenced by the other and the other way round. Special cases are full and no overlapping. With full overlapping any

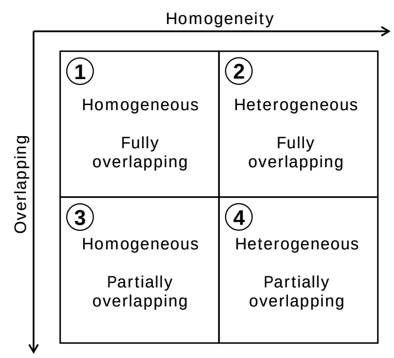

Fig. 1. Two research dimensions presented as a matrix.

simultaneous transmission of more than one system causes significant interference. In the trivial case of no overlapping, systems do not interfere.

In the following we want to concentrate on scenario (1) of figure 1. The evaluated systems follow the IEEE 802.16 protocol standard [1] forming a homogeneous, fully overlapping scenario.

A. IEEE 802.16 Frame Structure and Scheduler

The IEEE 802.16 Worldwide Interoperability for Microwave Access (WiMAX) standard defines a centrally controlled wireless communication protocol. A minimal IEEE 802.16 network is formed of two nodes as shown in figure 2 on the left. It consists of one central controller called Base Station (BS) and one Subscriber Station (SS). This can be extended to more complex deployments as shown in figure 2 on the right. Here a multi-cell scenario with one BS per cell and multiple SSs associated with each BS is shown.

In this work we only focus on systems consisting of one cell. IEEE 802.16 systems follow a periodic frame structure as shown in figure 3. Each frame is numberd with the running index n and starts with a preamble followed by the Frame Control Header (FCH). Besides general information about the system, the FCH provides the first part of the so called Map. The Map is formed by the scheduler deciding the exact structure of the current frame. It therefore contains several Information Elements (IE) describing which node should transmit or receive at which offset from frame start and which

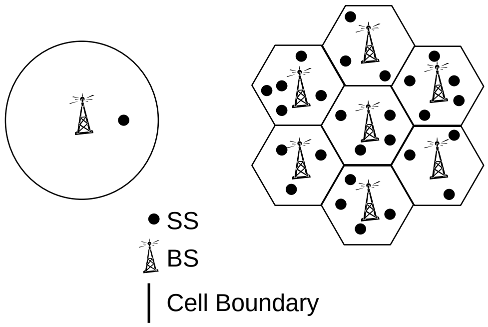

Fig. 2. Single- and multi-cell IEEE 802.16 system deployment.

Modulation and Coding Scheme (MCS) should be used. Only four IEs are transmitted in the FCH. If the Map contains more IEs they are transmitted in the first downlink burst.

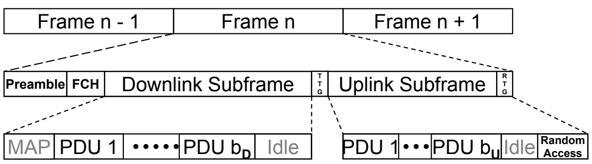

Fig. 3. IEEE 802.16 TDD frame structure.

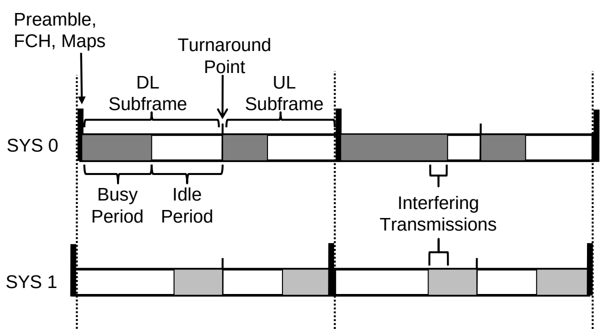

Fig. 4. Modified IEEE 802.16 TDD frame structure applying coexistence scheme.

IEEE 802.16 supports Frequency Division Duplex (FDD) and Time Division Duplex (TDD) operation but TDD is mandatory for license exempt operation. After the last downlink burst, the downlink subframe ends and after a Transmit / Receive Transition Gap (TTG) the uplink subframe starts. Besides data transmissions located in the uplink bursts the uplink subframe contains random access phases for initial access to the network and bandwidth requests. The frame ends with the Receive / Transmit Transition Gap (RTG).

The Map for each frame is created by the scheduler in the BS. For the downlink it inspects the queue and possible MCS for each SS and grants each node an appropriate share of the frame if possible. For the uplink the scheduler relies on information from the SSs to estimate their demands. A SS can register its traffic demands through bandwidth requests in the random access phase, through requests sent piggy-backed with other data transmissions or by sending bandwidth requests within an uplink burst assigned to it.

B. Related Work

The IEEE standard draft 802.16h [2] proposes methods for 802.16 system coexistence. It distinguishes between *coordinated* and *uncoordinated* operation. Coordinated operation uses a specified protocol allowing multiple systems to negotiate their resource usage. With uncoordinated operation no explicit messages are exchanged. A system has to sense the medium at the beginning of the frame. If it is busy the system is not allowed to perform any transmissions for the whole frame.

In [3] Berlemann and Walke propose a mechanism called Spectrum Load Smoothing (SLS). SLS is used to make channel occupancy more regular and therefore more predictable. It was evaluated for IEEE 802.11 systems. IEEE 802.11 protocol uses CSMA/CA causing a very irregular channel occupation. Using the extensions of IEEE 802.11e and additionally applying SLS assures a more regular channel occupation improving performance of coexisting systems.

In [4] Rapp evaluates the coexistence of HiperLAN/2 [5] systems. Scheduling policies creating *Silent Periods* as transmission opportunities for other systems are introduced. Results are derived by simulation. In the following a similar coexistence scheme is presented and evaluated analytically.

II. Coexistence Scheme Description

The following coexistence scheme allows two IEEE 802.16 systems to coexist in the same frequency channel by multiplexing their activity in time domain. Each system provides opportunities for the other systems to access the channel. Therefore each system has idle periods within its frame where it does not transmit. As shown in figure 3 idle periods are usually located at the end of the downlink and uplink subframes. These idle periods could be used by another system for transmissions. Figure 4 gives an example of how this could be achieved. If two systems have the same frame duration and the same turnaround point separating the downlink from the uplink subframe the second system could schedule its Protocol Data Units (PDUs) at the end of the subframes. It is assumed that each system reserves a dedicated part of the frame for the other system to transmit its broadcast information consisting of the Preamble, the FCH, and the Maps. A possible method for multiplexing broadcast channels of several cells for Global System for Mobile Communications (GSM) networks is described in [6] and could be applied.

Since the load of each system can vary between frames mutual interference can occur. Most likely the latest transmissions of SYS0 interfere with the earliest transmissions of SYS1. In the following we introduce a model of the proposed scheme and derive analytical results for the probability of simultaneous transmission in both systems.

Figure 5 shows a queueing network model of the proposed concept. The model is equal for downlink and uplink transmissions since transmission direction only introduces a constant

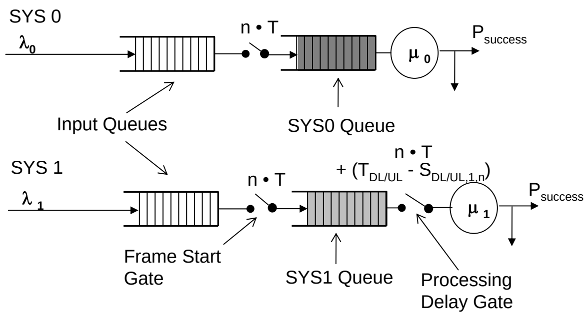

Fig. 5. Queueing model of proposed coexistence scheme.

offset from the frame start. Each job in the network represents a layer 2 PDU. Jobs arrive to the input queue from traffic sources at rate λ. At each subframe start the *Frame Start Gate* is opened and jobs are injected into the second queues. If at the beginning of a subframe the input queue has more jobs queued than can be processed in one frame duration T, only jobs with a total workload less than T pass the gate. The remaining jobs stay in the input queue.

SYS0 then starts immediately to process its queue until it is empty. Since the service period duration of the queue of SYS1 is known SYS1 starts processing its queue at a point in time assuring it finishes right before the end of the subframe. Therefore the *Processing Delay Gate* is opened. The server processes each job following a processing time distribution represented by its probability density function (PDF) $p(s)$ with mean value μ^{-1}. Jobs are only successfully processed and leave the system if only one server is operating during the total processing time of the job. Else processing fails and jobs are lost with probability $1 - P_{success}$.

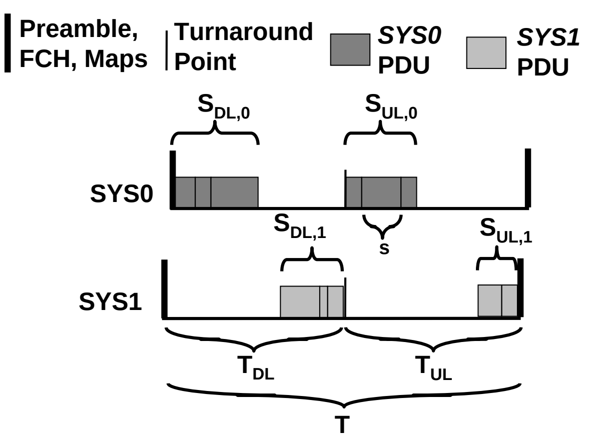

Fig. 6. Schematic example frame occupation and variable definition.

A. Analytical Evaluation

Figure 6 depicts different variables used in the following. For simplicity we assume Preamble, FCH, and Maps do not occupy any transmission time and that uplink and downlink subframes occupy 50% of the frame each. The subframe durations are therefore $T_{DL} = T_{UL} = T/2$.

Job processing, meaning interference on the channel, fails at two positions in the frame. If the service period duration in frame n of the downlink queue of SYS0 $S_{DL,0,n}(t)$ is not over before SYS1 starts processing its downlink queue at offset from frame start $T_{DL} - S_{DL,1,n}(t)$ interference occurs. Same happens if $T_{DL} + S_{UL,0,n}(t) > T - S_{UL,1,n}(t)$ meaning that SYS0 did not finish processing its uplink queue when SYS1 already started processing its uplink queue.

In the following we only focus on the downlink subframe since all results apply to the uplink with a constant shift of T_{DL}. All times are measured relative to the subframe start, therefore $0 \leq t \leq T_{DL}$. We assume stationary conditions in each frame, therefore the index n is omitted. $S_{DL,0}(t)$ and $S_{DL,1}(t)$ are random variables depending on the processing time distribution $p(s(t))$, the frame length T and the arrival process. If the arrival process is a Poisson process following results can be derived: The number of jobs k queued in the input queue at each frame start is Poisson distributed with the probability function $P(K = k) = \frac{(\lambda T)^k e^{-\lambda T}}{k!}$.

The service period duration is the sum of the processing times for all k jobs. The PDF can be therefore derived through k-fold convolution: $p(S_{DL,0}(t)|K = k) = p(s(t))^{(k)}$ with $f(x)^{(k)}$ being the k-fold convolution of $f(x)$ with itself. Applying the rule of total probability the unconditional PDF is

$$
\begin{aligned}
p(S_{DL,0}(t)) &= \sum_{i=0}^{\infty} P(K = i) p(S_{DL,0}(t)|K = i) \\
&= \sum_{i=0}^{\infty} P(K = i) p(s(t))^{(i)} \qquad (1)
\end{aligned}
$$

SYS1 queue processing always ends right before the end of the subframe. The moment when processing of the first job starts is interesting. The distribution is therefore mirrored on the y-axis and shifted by the subframe length T_{DL}: $p(S_{DL,1}(t)) = p(S_{DL,0}(-(t - T_{DL})))$.

Interference occurs if $S_{DL,0}(t) > S_{DL,1}(t)$ which means jobs from the queue of SYS0 are still processed while SYS1 already started processing its queue. The probability of simultaneous transmission is therefore $P(S_{DL,0}(t) > S_{DL,1}(t))$. This is only an estimate since a whole job is affected if above condition is true. Assuming $f(t) = p(S_{DL,0}(t))$ and $g(\tau) = p(S_{DL,1}(\tau))$ are independent then their joint PDF is $p(t, \tau) = f(t)g(\tau)$ and the probability of simultaneous transmission can be expressed as $P(ft) > g(\tau)) = \int_0^T f(t) \int_0^t g(\tau) d\tau dt$. The expected amount of time the systems transmit simultaneously is

$$
E_{P(f(t)>g(\tau))}[t - \tau] = \int_0^T f(t) \int_0^t g(\tau)(t - \tau) d\tau dt \qquad (2)
$$

III. Results

Two service time distributions are used for the evaluation. A first simple model assumes exponentially distributed service times. The second model takes different MCSs into account and is described in [7]. Here a single-cell scenario with uniformly distributed stations over a circle area is assumed. Different distances to the BS cause different MCSs. PDU size is fixed at 3144 bit. Table I summarises the resulting channel occupation times together with their probability to occur. The resulting mean processing time of a single PDU is $\mu^{-1} = 20.3725$ symbol durations each of length ($t_{sym} = 10/72ms$). In the following this is called the *WiMAX* distribution.

TABLE I
VALUES FOR *WiMAX* SERVICE TIME DISTRIBUTION

MCS	Relative circle segment surface [%]	Service time $[t_{sym}]$
BPSK $\frac{1}{2}$	39.4	33
QPSK $\frac{1}{2}$	20.56	17
QPSK $\frac{3}{4}$	27.95	11
16QAM $\frac{1}{2}$	4.1	9
16QAM $\frac{3}{4}$	5.15	6
64QAM $\frac{2}{3}$	0.92	5
64QAM $\frac{3}{4}$	1.92	4

We assume exponentially distributed PDU interarrival times. We therefore model a single arrival process per system as the superposition of all traffic flows.

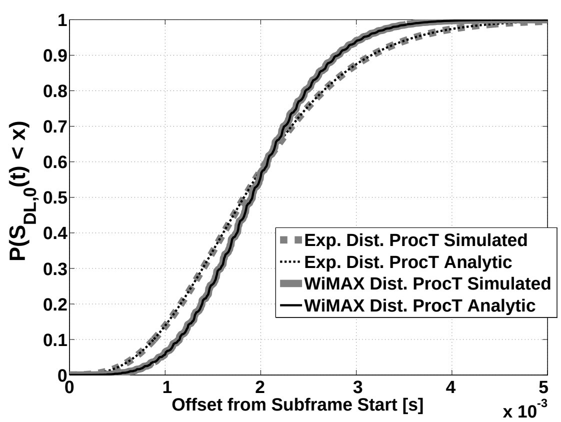

Fig. 7. Service period duration PDF for WiMAX and negative exponentially distributed service time. $\rho = 0.375, \mu^{-1} = 20.3725 t_{sym}, T = 10ms = 720 t_{sym}$

For validation of the analytic results figure 7 shows the Cumulative Distribution Function (CDF) of the service period duration of SYS0 for exponentially and *WiMAX* distributed service times. Total load factor ρ is kept constant at 0.375 per system. Mean processing time μ^{-1} is $20.3725 t_{sym}$ for both distributions. The results are derived analytically using (1) and by simulation. Both distributions show very similar statistic properties. Therefore in the following only exponentially distributed service times are evaluated. For exponentially distributed service time, $p(s(t))^{(i)}$ from (1) is the Erlang-k distribution.

Figure 8 shows the CDF of SYS0 service period duration together with the Complementary Cumulative Distribution

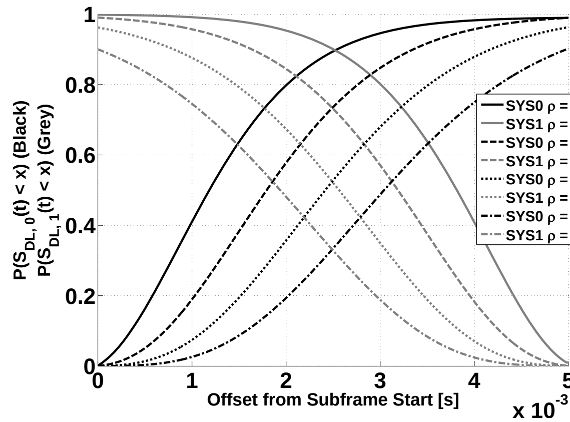

Fig. 8. Probability that SYS0 service period has finished together with the probability that SYS1 service period has not started yet for different load factors.

Function (CCDF) of SYS1 queue processing start. The total load ρ is varied. For example at $2ms$ offset from SYS0 frame start the probability that SYS0 has finished transmitting is 58% at load factor $\rho = 0.375$. With 90% probability SYS1 has not started transmitting at this point in time. As expected, with increasing load factor the service period durations increase. Therefore the probability of mutual interference caused by multiple systems processing a job increases. For a high load factor of $\rho = 0.625$ there is a probability of 7.5% that SYS0 has not finished transmitting at the end of the downlink subframe. This comes from the fact that (1) does not limit total service period duration to the subframe duration.

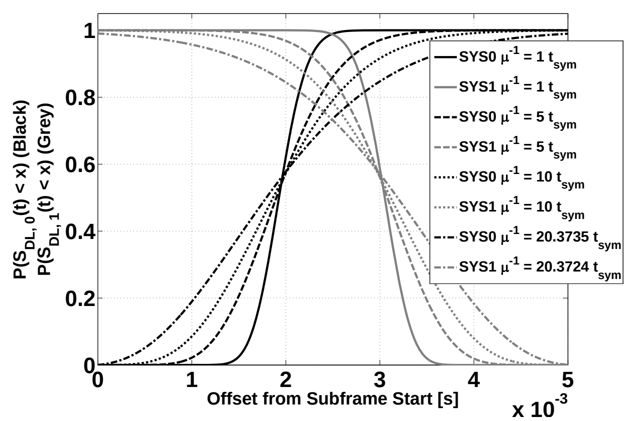

Fig. 9. Probability that SYS0 service period has finished together with the probability that SYS1 service period has not started yet for $\rho = 0.375$ and different mean processing times.

Figure 9 shows how service period duration of the queues varies at different mean job processing times. Load factor is fixed at $\rho = 0.375$. For a low mean processing time of $\mu^{-1} = 1 t_{sym}$ service period duration distribution shows a low variance. With increasing mean job processing time service period duration variance increases. The probability that service periods of both queues overlap therefore increases.

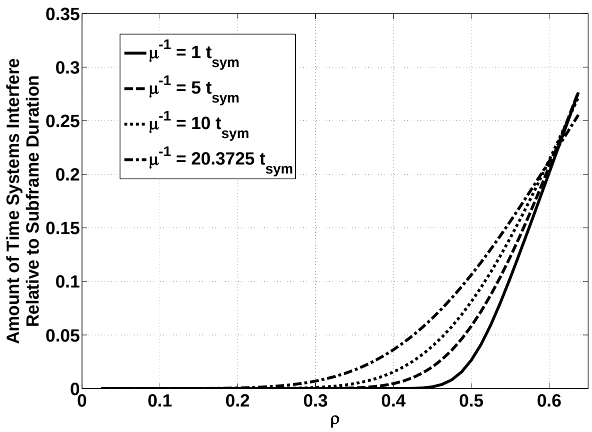

Fig. 10. Mean ratio of time the both systems transmit causing mutual interference normalized to total subframe length.

Figure 10 shows the mean ratio of time systems are transmitting simultaneously normalised to the subframe length T_{DL}.

Even at load factor $\rho = 0.5$ the probability that both systems transmit is only 11.5% at mean processing time $20.3725t_{sym}$. Still this means that both systems experience a bad channel state for this duration and potentially lose data. With decreasing processing time, interference probability decreases.

IV. Conclusion

A coexistence scheme has been presented which does not require carrier sensing before data transmission. With this scheme the system performance can be evaluated analytically. The presented approach can be implemented in IEEE 802.16 systems as a scheduling strategy without any changes to the standard. It has the drawback that for successful operation all systems at a given location have to follow it. Systems following the approach can estimate the impact of their scheduling decisions on own and overall performance. Presented results for mean probability of mutual interference can help to estimate if QoS demands can be satisfied. It was found that even for high loads interference probability is low. Since the probability of experiencing interference of aPDU depends on its position in the frame, derived results can be used to support traffic classes. High priority data can then be scheduled at the beginning (SYS0) or end (SYS1) of the subframe to assure high Signal to Noise and Interference Ratio (SINR) while best-effort traffic could be scheduled at offsets with higher interference probabilities.

For future work system performance for different traffic classes will be evaluated. How the mutual interference causing lower SINR affects system performance will be quantified. Since it is likely that not only IEEE 802.16 systems compete for spectrum access, presented scheme will be evaluated for heterogeneous scenarios.

Acknowledgment

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