IEEE 802.16 Coexistence through Regular Channel Occupation

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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, spectrum is made available to systems if a license holder is not using it at a given geographic location or time. In this case multiple systems can compete for spectrum access. In this paper we present an approach how multiple IEEE 802.16 systems can coexist in the same frequency band. The key idea is to define rules how the systems can schedule their transmissions to achieve more regular and therefore more predictable channel occupation. The approach does not require carrier sensing before normal data transmission. Analytic and simulation results are presented showing how systems can estimate available capacity and the impact of their behaviour to own and overall performance. Therefore results for the collision probability are derived.**

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 simultaneous transmission of more than one system causes data loss. In the trivial case of no overlapping systems do not interfere.

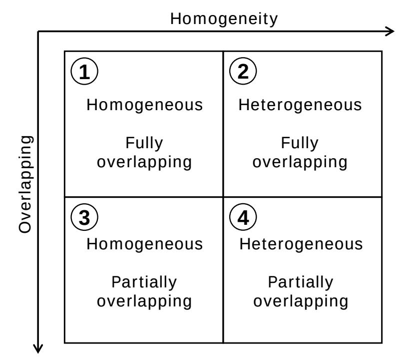

Fig. 1. Two research dimensions presented as a matrix.

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 SS 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 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 Modulation and Coding Scheme (MCS) should

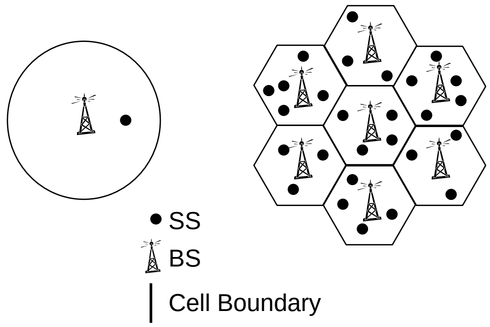

Fig. 2. Single- and multi-cell IEEE 802.16 system deployment.

be used. Only four IEs are transmitted in the FCH. If the Map contains more IEs they are transmitted in the first downlink burst.

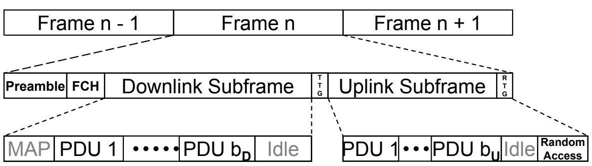

Fig. 3. IEEE 802.16 TDD frame structure.

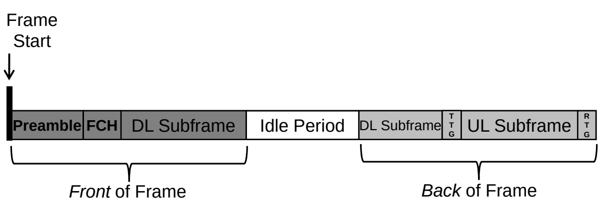

Fig. 4. Modified IEEE 802.16 TDD frame structure applying coexistence scheme.

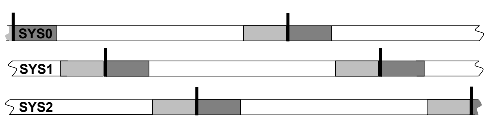

Fig. 5. Three systems create idle periods and shift their frame start to allow coexistence.

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 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 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.

IEEE 802.16 already applies certain regularity by using a periodic frame structure. Still there are further improvements possible to make channel access even more predictable. Such a concept is presented in the next section.

II. Coexistence Scheme Description

The following coexistence scheme allows multiple IEEE 802.16 systems to coexist 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. Figure 4 shows the modification done to the periodic frame structure of the IEEE 802.16 system. Goal of the modifications is to form a continuous idle period in the middle of the frame. Therefore the turnaround point between downlink and uplink subframe has to be adjusted dynamically. The turnaround point is set right after the last downlink Protocol Data Unit (PDU) has been transmitted. The part of the frame before the idle period is called the *Front* of the frame, the one behind it the *Back*. In the example given in figure 4 downlink transmissions have a longer total transmission time than uplink transmission. The downlink subframe is therefore split between *Front* and *Back* of the frame.

To benefit from the idle periods systems have to shift their frame starts as shown in figure 5. Frame starts are shifted to assure maximal offset in time. Here we assume all systems have the same frame length T. If there are M systems each has to shift its frame start by T/M. We assume mechanisms exist to detect other systems and their frame configuration to achieve shifted frame starts. For example this could be done by CS together with an autocorrelation function detecting the known preamble sequence at frame start. Shifting the frame start is initiated by the BS and signalled to the associated SSs.

It may result in temporal loss of connectivity. Still the impact can be neglected since it is only required when new systems start operating in the area or previously active systems are switched off.

Since the load of each system can variate between frames collisions can occur. With this scheme most likely transmissions at the edge of the *Back* and *Front* of the frame collide. The most sensible data, including the Maps at the beginning of the frame, will less likely collide. In the following we introduce a model of the proposed scheme and derive analytical results for the probabilities of possible collisions.

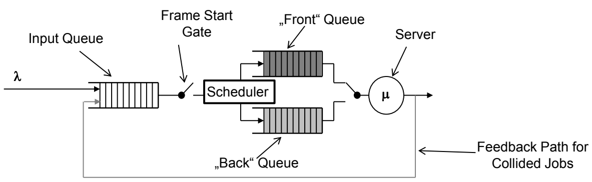

Fig. 6. Queueing model of proposed coexistence scheme.

Figure 6 shows a queueing network model of the proposed concept for one system. Each job in the network represents a layer 2 PDU. Jobs arrive to the input queue either from external traffic sources at rate λ or are fed back because of unsuccessful processing. At each frame start the *Frame Start Gate* is opened and jobs are distributed equally between *Front* and *Back Queue*. First half of the jobs is injected into the *Front*-, the second half into the *Back Queue*. If the number of jobs is not even, one more job is put into the *Front Queue*. If at the beginning of a frame 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.

The system then starts immediately to process the *Front Queue* until it is empty. Since the service period duration of the *Back Queue* is also known the system starts processing the *Back Queue* at a point in time assuring it finishes right before the start of the next frame. The server processes each job following a processing time distribution represented by its probability density function (PDF) $p(s)$ with mean value μ^{-1}. Described queueing network is present for each system. 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 reenter the input queue with probability $P(C)$. The input queue is ordered oldest job first.

A. Analytical Evaluation

For analytical analysis we assume the feedback path shown in figure 6 is not present and jobs not processed successfully are lost. Figure 7 depicts different variables used in the following. In the case of two systems SYS0 and SYS1 job processing, meaning collision on the channel, mostly fails at two positions in the frame. If the service period duration in frame n of the *Front Queue* of SYS0 $S_{F,0,n}(t)$ is not over before SYS1 starts processing its *Back Queue* at offset from frame start $T/2 - S_{B,1,n}(t)$ collisions occur. Same happens if

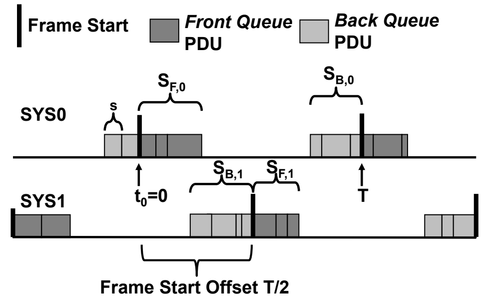

Fig. 7. Two systems shift their frame start to allow coexistence.

$T/2 + S_{F,1,n}(t) > T - S_{B,0,n}(t)$ meaning that SYS0 did not finish processing its back queue when SYS1 already started processing its front queue. Additionally for high loads *Front Queue* processing of SYS0 could extend beyond SYS1 frame start and collide with jobs from the *Front Queue* of SYS1. Same can happen with jobs processed from *Back Queue*. All times are measured relative to the frame start of SYS0, therefore $0 \leq t \leq T$. We assume stationary conditions in each frame, therefore the index n is omitted. $S_{F,0}(t)$, $S_{B,0}(t)$, $S_{F,1}(t)$, and $S_{B,1}(t)$ 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: Since no feedback path is present, the number of jobs k queued in the input queue at each frame start is Poisson distributed with the probability function $P(K = k) = \frac{(\lambda T)^k e^{-\lambda T}}{k!}$. In the following for the queue q we use the index F for the *Front*- and B for the *Back Queue*. Since $\lceil k/2 \rceil$ jobs are put into queue F and $\lfloor k/2 \rfloor$ into queue B

$$\begin{aligned} P_F(K = k) &= P(K = 2k) + P(K = 2k - 1) \\ &= \frac{(\lambda T)^{2k} e^{-\lambda T} (1 + 2k(\lambda T)^{-1})}{(2k)!} \end{aligned} \tag{1}$$

$$\begin{aligned} P_B(K = k) &= P(K = 2k) + P(K = 2k + 1) \\ &= \frac{(\lambda T)^{2k} e^{-\lambda T} (2k + 1 + \lambda T)}{(2k + 1)!} \end{aligned} \tag{2}$$

describe the probability to find k jobs queued in q at frame start. 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: $p(S_{q,m}(t)|K = k) = p(s(t))^{(k)}$ with $f(x)^{(k)}$ being the k-fold convolution of $f(x)$ with itself. Applying the rule of total probability the unconditional PDF is

$$\begin{aligned} p(S_{q,m}(t)) &= \sum_{i=0}^{\infty} P_q(K = i) p(S_{q,m}(t)|K = i) \\ &= \sum_{i=0}^{\infty} P_q(K = i) p(s(t))^{(i)} \end{aligned} \tag{3}$$

For times measured from frame start of SYS0 the function has to be shifted: $p(S_{q,m}(t - \frac{mT}{M}))$. *Back Queue* processing always ends right before the start of the next frame. The moment when processing of the first job starts is interesting. The distribution is therefore mirrored on the y-axis and shifted by the frame length T: $p(S_{B,m}(-(t-T)))$. In the following just the collision between SYS0 *Front Queue* and SYS1 *Back Queue* jobs is evaluated. Other results can be derived analogously. Collisions occur if $S_{F,0}(t) > S_{B,1}(t)$ which means jobs from the *Front Queue* of SYS0 are still processed while SYS1 already started processing its *Back Queue*. The collision probability is therefore $P(S_{F,0}(t) > S_{B,1}(t))$. This is only an estimate since a whole job collides if above condition is true. Assuming $f(x) = p(S_{F,0}(t))$ and $g(y) = p(S_{B,1}(t))$ are independent then their joint PDF is $p(x,y) = f(x)g(y)$ and the collision probability can be expressed as $P(f(x) > g(y)) = \int_0^T f(x) \int_0^x g(y)dydx$. The expected amount of time the systems are in collision state is

$$E_{P(f(x)>g(y))}[x-y] = \int_0^T f(x) \int_0^x g(y)(x-y)dydx \quad (4)$$

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 [4]. Here a single-cell scenario with uniformly distributed stations over a circle area is assumed. Different distances to the BS cause different MCSs. MAC-PDU size is fixed at 3144 bit. Table I summerizes 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 $t_{sym} = 10/72ms$. 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. Two systems are evaluated with totally overlapping coverage area.

For validation of the analytic results figure 8 shows the Cumulative Distribution Function (CDF) of the service period duration of queue F 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 $20.3725t_{sym}$ for both distributions. The results are derived analytically using (3) and by simulation. Both distributions show very similar

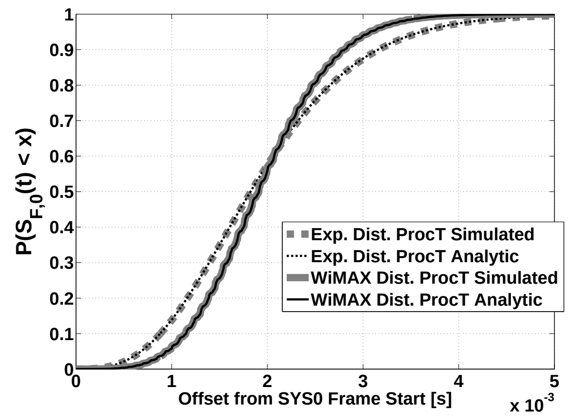

Fig. 8. *Front Queue* service period duration PDF for WiMAX and negative exponentially distributed service time. $\rho = 0.375, \mu^{-1} = 20.3725t_{sym}, T = 10ms = 720t_{sym}$

statistic properties. Therefore in the following only exponentially distributed service times are evaluated. For exponentially distributed service time, $p(s(t))^{(i)}$ from (3) is the Erlang-k distribution.

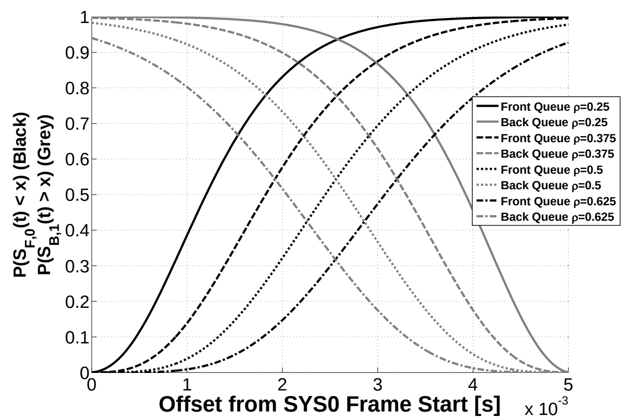

Fig. 9. Probability that SYS0 *Front Queue* processing has finished together with the probability that SYS1 *Back Queue* processing has not started yet for different load factors.

Figure 9 shows the CDF of SYS0 queue F service period duration together with the Complementary Cumulative Distribution Function (CCDF) of SYS1 queue B processing start. The total load ρ is varied. For example at $2ms$ offset from SYS0 frame start the probability that SYS0 has finished processing queue F is 58% at load factor $\rho = 0.375$. With 90% probability SYS1 has not started processing queue B. As expected, with increasing load factor the service period durations for queues F and B increase. Therefore collision probability 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 processing queue F when the next frame of SYS1 starts at $5ms$. In this case SYS1 would not be able to transmit for a whole frame since its FCH would be lost due to collision. A possible solution would be to limit service period duration of queues F and B to $T/2 = 5ms$.

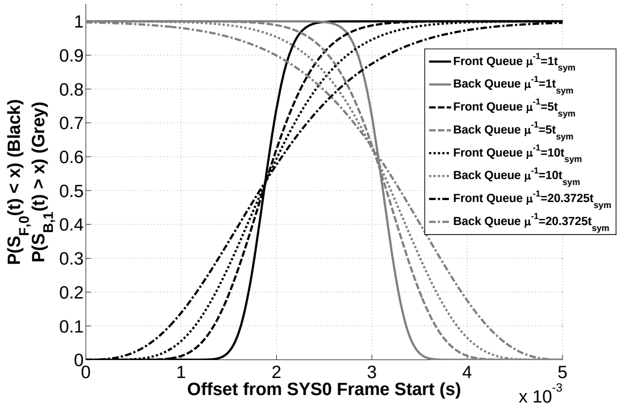

Fig. 10. Probability that SYS0 *Front Queue* processing has finished together with the probability that SYS1 *Back Queue* processing has not started yet for $\rho = 0.375$ and different mean processing times.

Figure 10 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 $\mu^{-1} = 1t_{sym}$ 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.

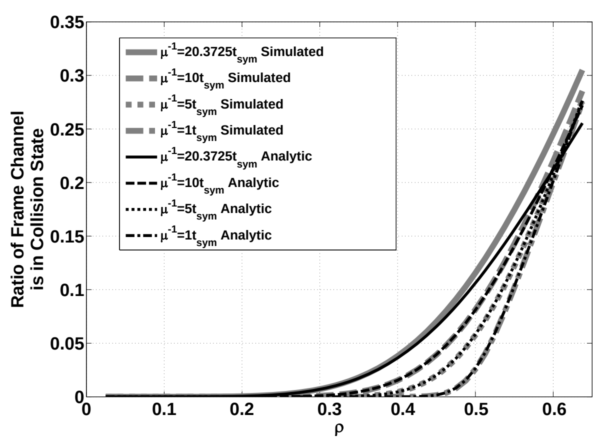

Fig. 11. Mean ratio of time the frame is in collision state because more than one system is transmitting.

Figure 11 shows the mean ratio of time the frame is in collision state. It has been derived analytically using formula (4) and verified by simulation. Formula (4) was evaluated for collisions of SYS0 queue F with SYS1 queue B and multiplied by two for collisions in the second half of the frame. It has then been divided by T to be normalised to the frame length. The analytic results therefore do not take into account collisions happening at high loads when a service period duration of one system extends beyond the frame start of another system. The difference between simulated and analytic results therefore increases as the load increases.

Even at load factor $\rho = 0.5$ the channel is only 11.5% of the time in collision state at mean processing time $20.3725t_{sym}$. Still this means that both systems lose data for that duration. With decreasing processing time, collision 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 collision probability can help to estimate if QoS demands can be satisfied. It was found that even for high loads collision probability is low. Since the collision probability 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 or end of the frame to assure low collision probability while best-effort traffic could be scheduled at offsets with higher collision probabilities.

For future work system performance for different traffic classes will be evaluated. Also the influence of the feedback path modelling Automatic Repeat Request (ARQ) which has been omitted in this work will be evaluated. 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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