Mitigating Interference between IEEE 802.16 Systems Operating in License-exempt Mode

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Abstract. A rudimentary approach to mitigate interference issues in license-exempt 802.16 systems is presented. This approach operates by permitting each *Base Station* (BS), and associated *Subscriber Stations* (SSs) to remain inactive for a specified fraction of the time. Other systems can then transmit with a reduced likelihood of interference. A simulator was developed to determine how this system performs. The results show that the throughput of the system is very sensitive to the fraction of time each BS is active; the system throughput is maximised when each BS is active less than 40% of the time for the scenarios studied. The results demonstrate a discrepancy between uplink and downlink throughput which can be attributed to the greater amount of overheads in the uplink. Finally, the results show that broadcast information being transmitted periodically at full power has a significant detrimental impact on the system.

1 Introduction

Delivering broadband connectivity to every house and business is a challenging issue for broadband access providers. In many countries around the globe wired broadband connections like *Digital Subscribers Line* (DSL) or fibre-optics have been deployed, particularly in large urban areas. Wireless solutions can complement these wired technologies to deliver broadband access in less densely populated areas and developing regions.

While broadband access solutions have been available for some time now, standardised solutions have only recently become available and it is anticipated that they will have a significant impact on the market. IEEE 802.16 is a relatively new broadband wireless access standard but it is receiving considerable interest at present. It provides the setting for this work.

In general, the available wireless technologies can be divided into two mode of operation: licensed mode of operation, and license-exempt mode of operation. In licensed mode the spectrum is tightly controlled by a regulator, where licenses are issued to individual operators which provide exclusive access to some part of the frequency spectrum. By providing exclusive access to spectrum, this approach ensures that there is no interference between operators. In license-exempt mode spectrum is not assigned to any particular operator; the operators require no license to use this spectrum. However, some regulations may be applied for using these bands, such as limiting the transmit power and the coverage areas. The 2.4 GHz *Industrial, Scientific and Medical* (ISM) band and the *Unlicensed National Information Infrastructure* (U-NII) bands are examples of license-exempt bands.

As license-exempt spectrum is largely unregulated interference issues can arise. This interference can arise from: selfish use of the medium, the lack of cooperation between users, and the differences between systems characteristics and architectures. This interference affects the operation of wireless systems using license-exempt spectrum and can severely degrades their performance.

IEEE 802.16 has been designed such that it can operate in license-exempt spectrum. The IEEE 802.16 system consists of a *Base Station* (BS) and one or more *Subscriber Stations* (SSs) distributed over a geographical area with a radius of typically up to a few kilometres. In the case in which there are a limited number of channels available interference between different IEEE 802.16 systems can arise. In this paper we study the performance of a number of IEEE 802.16 systems operating in license-exempt mode of operation. More specifically, we wish to investigate the performance of an approach which can be used to mitigate the impact of such interference. This approach is based on introducing sleep intervals for each BSs. Initially, these sleep intervals are created randomly.

A rudimentary Java simulator was implemented to determine the system performance. The simulator was designed to simulate a number of 802.16 systems operating in license-exempt mode in the same geographical area on the same channel. Furthermore, the interference mitigation approach described below is simulated. The simulator can determine the amount of interference between these systems and system performance metrics such as the throughput per SS.

The reminder of the paper is organized as follows: in section 2 related work is discussed. Section 3 gives a brief introduction to the IEEE 802.16 standard. Section 4 describes the simulator and results obtained from using same. Finally, conclusions and future work is presented in section 5.

2 Related Work

There have been a few contributions to the literature on the performance evaluation of the 802.16 systems. The authors in [1], [2] investigated the performance of ETSI HiperMAN and IEEE 802.16a. Their results showed that the *Medium Access Control* (MAC) functions introduced an overhead of approximately 10%. Also, they have showed the efficiency gains that can be achieved by using the optional 802.16 packing and fragmentation features. In [6] the authors took a different perspective of 802.16 system performance and showed how different modulation and coding schemes have an impact on delay and throughput of the system.

In [7] an architecture for supporting *Quality of Service* (QaS) in 802.16 system was proposed. This architecture was based on priority scheduling and dynamic bandwidth allocation. No experiential work was presented to demonstrate the operation of this approach.

To the best of our knowledge no work has been published focusing on interference issues in IEEE 802.16 license-exempt systems. However, there have been contributions to the literature addressing interference problems for other radio systems, such as WLAN, HiperLAN/2 and Bluetooth. Several solutions have been proposed for such interference problems.

The authors in [3] proposed spectrum etiquette that requires a number of actions and rules, to facilitate the coexistence of wireless systems in unlicensed frequency bands. They examined this approach in three different radio systems, all of which support the *Listen Before Talk* (LBT) mechanism. Their results showed that using LBT mechanisms cooperation between systems can be achieved and interference significantly reduced. In [4] the authors looked into the interference problem between the IEEE 802.11a and the HiperLAN/2 systems which are operating in the 5.1 GHz band. They proposed a solution based on cooperation between these two systems and they concluded that this can be achieved by introducing minor changes to both standards.

While the above contributions are interesting and somewhat relevant in the context of this discussion, the architecture of the radio systems they have investigated differs from that of the IEEE 802.16. For this reason, the techniques that have been devised are not applicable here.

The IEEE 802.16 community is aware of the interference issue between the IEEE 802.16 license-exempt systems. For this reason, they have initiated a work activity focusing on mitigating interference in these systems. This work will lead to the development of the IEEE 802.16h standard. This work is still at an early stage, however; it is anticipated that the standard will be developed in the first quarter of 2007.

3 The IEEE 802.16 Standard

Broadband Wireless Access (BWA) technology has been around for a long time, but the lack of standards made the technology limited and expensive. The development of IEEE 802.16 standard is expected to result in significant changes to the costs of BWA systems due to economies of scale that can result from standardisation. This, in turn, is expected to stimulate significant growth in the BWA market.

The first 802.16 standard was published in April 2002. The standard defines the MAC and physical (PHY) layers, operating in licensed spectrum between 10 and 66 GHz. It requires *Line of Sight* (LOS) connectivity and supports up to 134 Mb/s of shared capacity per sector [5]. In April 2003, the IEEE 802.16a standard was published. It is an amendment to the IEEE 802.16 standard which provides additional PHYs for 2-11 GHz licensed and license-exempt operation and enhancements to the MAC to support a mesh topology. The standard supports *Non Line of Sight* (NLOS) connectivity and up to 70 Mb/s per sector. The IEEE 802.16-2004 [9] was released in October 2004. In essence, this integrates the original 802.16 standard and 802.16a amendment; it also provides some enhancements to improve the operation of indoor antennas in the 2-11 GHz band.

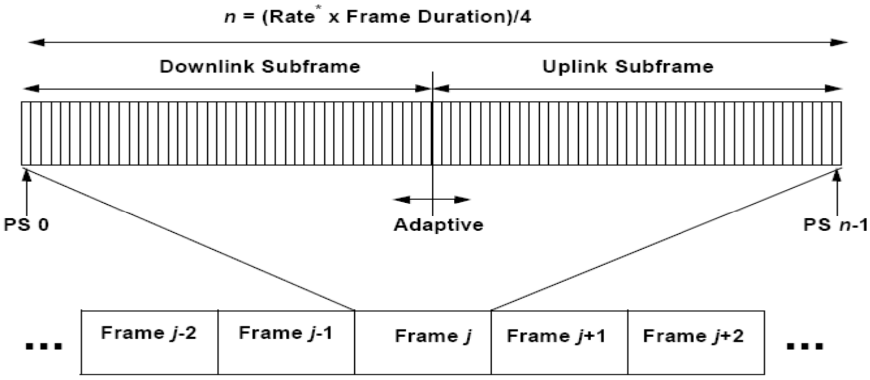

Fig. 1. OFDM Frame Structure with TDD

IEEE activity is still ongoing with much energy being devoted to adding mobility to 802.16 systems right now. The proposed IEEE 802.16e is an amendment to the standard which will provide support for mobility at vehicular speeds; it is due for completion in Summer 2005.

In the following subsection an overview of IEEE 802.16 is given. This is followed by a discussion of the 802.16 MAC which is particularly relevant to this work. This section ends with a short discussion of the standardised *Dynamic Frequency Selection* (DFS) mechanism which can be used to mitigate interference problems in some cases.

3.1 IEEE 802.16 System Overview

The IEEE 802.16 system consists of a BS and a number of SSs. It is a connection-oriented system with QoS support which is tightly controlled by the BS. The system typically operates in a point-to-multipoint fashion, although the standard does provide mesh network support.The uplink and downlink channels are *Time Division Duplexed* (TDD) or *Frequency Division Duplexed* (FDD). Four PHY layers are specified in the standard:

- WirelessMAN-SC: 10-66 GHz single carrier LOS required;
- WirelessMAN-SCa: 2-11GHz based on a single carrier, with NLOS support;
- WirelessMAN-OFDM: 2-11 GHz based on *Orthogonal Frequency Division Multiplexing* (OFDM) modulation, designed for NLOS operation [8];
- Wireless-MAN-OFDMA: 2-11 GHz based on OFDM modulation with support of *Orthogonal Frequency Division Multiple Access* (OFDMA) designed for NLOS operation.

The standard supports a number of modulation schemes such as QPSK, 16-QAM and 64-QAM.

For each PHY, a *physical slot* is defined. In the case of the OFDM PHYs, this corresponds to the transmission of a single OFDM symbol. A number of physical slots are grouped into so-called *mini-slots*: these are the smallest unit that can be used for resource allocation.

The standard makes specific stipulations regarding license-exempt operation. In license-exempt mode, TDD multiplexing should be used with a frame duration of 0.5ms, 1ms or 2ms [9] with a channel bandwidth of 20MHz.

3.2 MAC overview

The IEEE 802.16 MAC is responsible for channel access and bandwidth allocation for different SSs. Medium access is controlled by the BS. In TDD operation, each frame consists of a *downlink* (DL) subframe and an *uplink* (UL) subframe as illustrated in figure 1. The downlink subframe is sent by the BS to SSs and consists of header information followed by data bursts transmitted to one or more SSs. More specifically, the DL *Protocol Data Unit* (PDU) contains a DL preamble used for synchronization, a *Frame Control Header* (FCH) and a number of DL data bursts. The first DL burst may contain information to be broadcast to all stations in the system such as a DL map, an UL map, a *Downlink Channel Descriptor* (DCD) and an *Uplink Channel Descriptor* (UCD). These messages are broadcast with full power to all of the SSs associated with a particular BS. The uplink consists of some time reserved for ranging and transmission of bandwidth requests, followed by the transmission of a number of UL PDUs by different SSs. Each UL PDU consists of a preamble and an UL burst.

IEEE 802.16 MAC supports various scheduling services classes for allocating bandwidth. These classes are defined as *Unsolicited Grant Service* (UGS), *Real-time Polling Service* (rtPS), *Non-real-time Polling Service* (nrtPS) and *Best Effort Service* (BES). There is also provision for an *Automatic Repeat Request* (ARQ) mechanism in the 802.16 MAC; this facilitates reliable data transfer.

3.3 DFS Overview

When using IEEE 802.16 in license-exempt operation, the U-NII license-exempt bands should be used. In these bands interference between users operating on the same channel can arise. The DFS mechanism was added to the 802.16 MAC to enable systems to avoid interference by automatically switching to an unused channel. The DFS mechanism is mandatory for license-exempt operation, where systems should detect and avoid primary channel users to avoid interference between them.

As illustrated in Figure 2(a) three channels are distributed between BSs A, B and C using DFS. In Figure 2(b) the number of BSs is increased to 5 resulting in more BSs than the available number of channels.In this case, DFS will be unable to distribute the available channels between the BSs. Thus, interference issues will arise unless some measures are taken to prevent them.

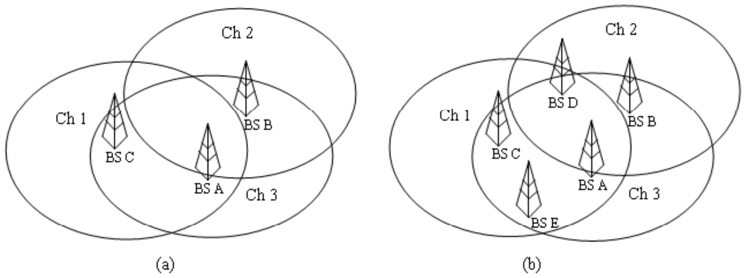

Fig. 2. Spectrum Distributions Using DFS

4 Simulation and Results

A simulator was developed throughout this work to model a number of different IEEE 802.16 systems operating in close proximity to each other on the same channel. In the following subsection an overview of the simulator is given followed by results and discussion subsection.

4.1 The IEEE 802.16 License-exempt Mode Simulator

The simulator that was developed can model a number of different 802.16 systems operating in point-to-multipoint mode. Specific aspects of the 802.16 MAC and PHY are modelled such as scheduling, power control and interference are modelled in the simulator. To reduce the interference between the IEEE 802.16 systems, a rudimentary approach based on introducing random sleep times for each BS was used. The following assumptions were made while designing the simulator:

- The system is *symmetric* in the sense that the same amount of time is allocated to uplink transmission and downlink transmission;
- The system is *synchronised* in the sense that all BSs are assumed to operate from the same clock;
- The system is operating in saturated conditions, meaning that there is always data to be transmitted to and from each SS;
- All BSs use the same frame structure and operate on the same channel.

The scheduling mechanism is designed to distribute resources equally between the SSs in the system. In the simulator, it was assumed that each frame can accommodate a fixed number of SSs. The number of SSs that can be served for each of the permitted frame durations is shown in Table 1.

The TDD frame duration is divided between the downlink and the uplink subframes; the duration of the downlink preamble is 2 OFDM symbols and the FCH is transmitted using one OFDM symbol. In the uplink, the preamble is 1 OFDM symbol. There is a bandwidth contention period of 1 mini-slot and an initial ranging contention period of 4 mini-slots. The downlink and uplink preambles and the contention periods are called the TDD frame overhead; the parameters defined in Table 2 can be used to determine the amount of time

Frame Duration	Downlink SSs	Uplink SSs
0.5ms	5	5
1ms	10	10
2ms	20	20

Table 1. Number of SSs per frame

consumed by this overhead. The downlink overhead consists of 3 OFDM symbols, 2 for preamble and 1 for FCH, where the uplink overhead consists of 2 contention periods of the same duration as 10 physical-slots, and 10 OFDM symbols divided between the SSs as uplink preambles.

The BS capability to become inactive for one or more frame durations is useful in the context of the license-exempt environment as it provides an opportunity for others on the same channel to transmit. If all BSs were to transmit continuously, then there could be very substantial interference for all users in the system, rendering it quite useless for all users. To avoid this, a probabilistic approach in which each BS remains inactive for some period of time is used. More specifically, each BS is configured with an *activity factor* which controls what fraction of the time the BS is active for. For each frame, the probability of the BS being active is equal to the activity factor.

The BSs schedule their traffic using a rudimentary scheduling approach, where the BS looks at how many SSs it has and what frame duration it uses. Then it finds the *Lowest Common Multiple* (LCM) between the number of SSs and the number of SSs per-frame according to Table 1. After that, the LCM is divided by the number of subscribers. The result is the number of different schedules required. The schedules are then constructed by placing the SSs consecutively into frames as shown in Figure 3,

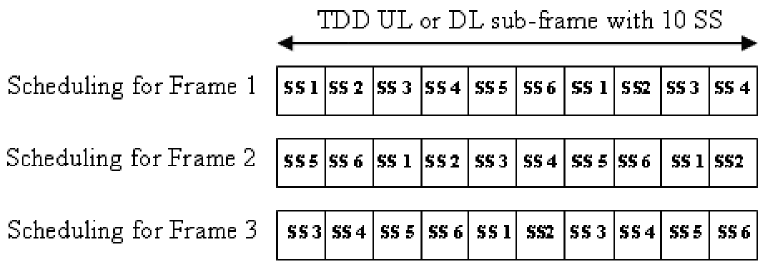

Fig. 3. Schedules for Six SSs

The downlink and the uplink transmission powers are calculated at the system start-up using a power control algorithm, which is based on the well-known Friis power transmission equation. Determination of interference is also based on power calculations. This is done by comparing the receiver power of signals which are transmitted simultaneously. If the difference between these signals exceeds $> 5dB$, then the signal can be received correctly; otherwise interference is deemed to have taken place.In the simulations below, each BS is active of a defined period of time. A random process controls which specific frames a station is active for, So, while the fraction of time a BS is active is defined, the particular active and idle frames for a BS vary from simulation to simulations. It is worth nothing that an active time of 100% corresponds to the system being active all time; this is how the system would behave if there was no support for this sleep mode.

Parameter	Value
Wavelength	5.1238cm
Transmitter Gain	15dBm
Receiver Gain	15dBm
System Loss	1
Maximum Transmission Power	1mW
Bit Rate	46.08 Mb/s
OFDM Symbol Time	12.5μs
TTG and RTG	100μs
Mini-slot Duration	0.347μs
Channel BW	20MHz

Table 2. Simulation Parameters

4.2 Results and Discussion

To study the performance of IEEE 802.16 licensed exempt systems, we used the simulation parameters specified in table 2. Random network topologies consisting of 4 BSs and 30 SSs per BS were used in these experiments. The network was located in a 100km^2 area as illustrated in Figure 4.

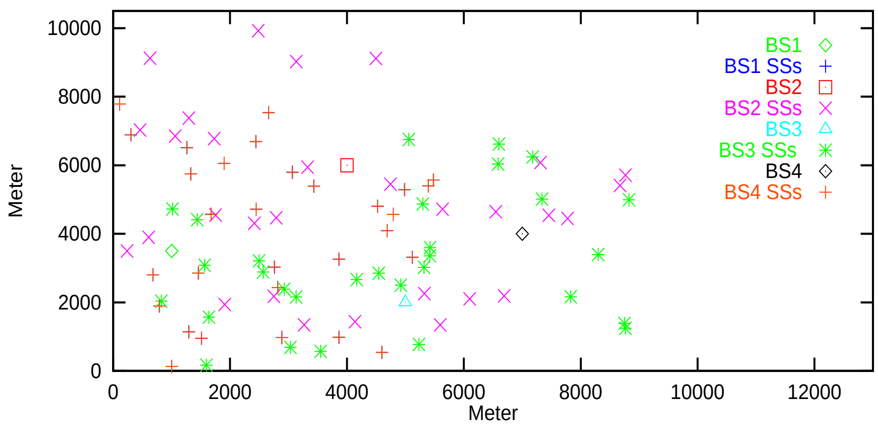

Fig. 4. SSs Throughput at 50% Active Time

Several simulations were performed each lasting 60 sec of simulation time. The results ware aggregated and analysed to provide graphical representation as shown in the following figures.

Figures 6 and 7 show the overall system throughput and the throughput per BS respectively. It can be seen from these figures that the performance of the system varies significantly with the activity factor. When the activity factor is low, the overall system throughput is quite low as each BS is inactive much of the time. When the activity factor is high, the overall throughput is also low, as there is much interference and few successful transmissions are made. There is a region around 25% to 40% during which time the throughput is maximised. At this point, every BS gets approximately 13% of the throughput that could be obtained if a BS had no interference issues. This can be compared to a scheme in which there is co-ordination between the BSs and the time could be divided such that each BS is active for 25% of the time. In this case, each BS could obtain 25% of that which it would obtain if it had exclusive access to the medium.

In Figure 8, the variation in the SSs throughput curve with the activity factor can be seen. This graph exhibits similar behaviour to that of the previous graphs - the throughput is low for low and high activity factors, and is highest for some intermediate values. It can also be seen from this graph that there is a considerable variation in the throughput achieved by each SS, as evident from the significant difference between the minimum and maximum. Figure 9 shows that the average system downlink and uplink throughput coincides with figure 6 and figure 7 and also shows the expected difference between the downlink and the uplink throughput due to the uplink overheads.

Figures 10 and 11 show the overall numbers of collisions on the system. From these results, it can be seen that there is a very linear relationship between the activity factor and the number of collisions in the system. Further, it can be seen that the collisions are divided pretty equally between all the BSs in the system. The numbers of collisions experienced by the SSs is shown in Figure 12. As with the previous graph, there is a quite linear increase in the mean number SS collisions with the activity factor. Also, as with the SS throughput, there is a significant variance in the amount of collisions that can be experienced by a SS. Figure 13 shows the average uplink and downlink collision rate. It is clear from the figure that most of the collisions occur in the downlink. It is worth noting, however, that in many cases a collision in the downlink can result in a SS missing an opportunity to transmit: if the SS does not receive the UL Map correctly, it does not know when to transmit and hence misses a transmission opportunity. The much greater number of collisions in the downlink can be attributed to the fact that some of the downlink information is transmitted at full power.

In Figure 14 the nodes in the system have been classified into those that obtain high throughput, medium throughput and low throughput. The results depicted in Figure 14 were generated using an activity factor of 50%. This classification is performed based on the difference from the overall mean throughput: nodes that obtain throughput of less than 50% of the mean throughput are deemed low throughput and nodes that obtain throughput of 50% greater than

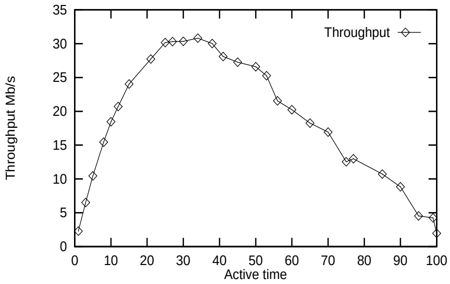

Fig. 6. Overall System Throughput

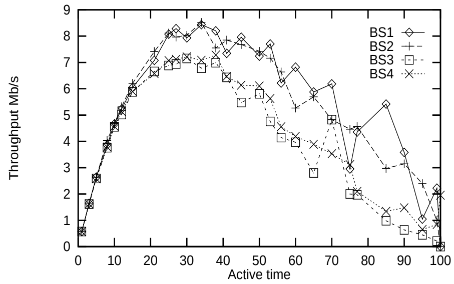

Fig. 7. Throughput per BS

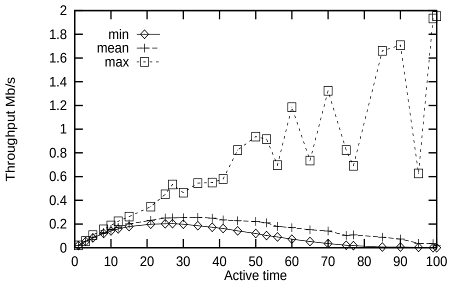

Fig. 8. Min, Ave, Max Throughput

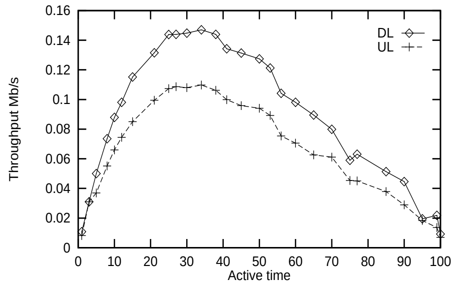

Fig. 9. Average DL and UL Throughput

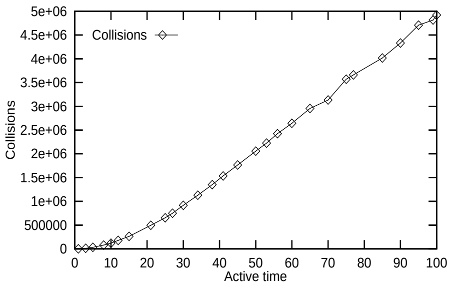

Fig. 10. Overall System Collisions

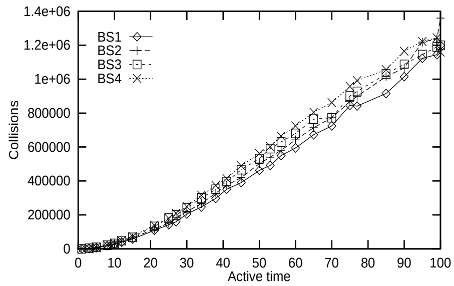

Fig. 11. Collision per BS

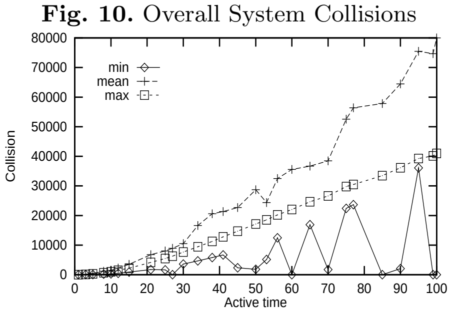

Fig. 12. Min, Ave, Max Collision

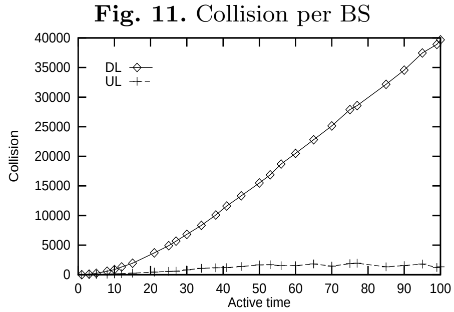

Fig. 13. Average DL and UL Collision

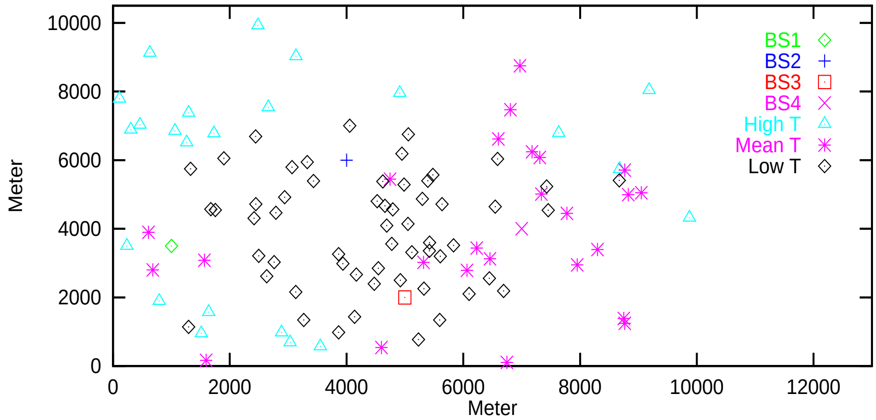

Fig. 14. SSs Throughput at 50% Active Time

the mean are considered high throughput. It is clear from the results that the nodes which are located in the centre of the area obtain lower throughput and those at the extremities obtain significantly higher throughput. This is not surprising as those at the centre are more likely to experience interference.

5 Conclusion

This work is an initial study of an approach to mitigate interferences issues that may arise in 802.16 systems operating in license-exempt operation. The approach is a natural one; it operates by enabling some BSs (and their associated SSs) to remain inactive, or asleep, for some periods of time, thereby permitting others in the same geographical area to use the limited available spectrum.

In this contribution, a rudimentary simulator which we have developed to simulate this scenario has been described. The simulator can be used to simulate a number of BSs and their associated SSs operating in the same geographical area. The simulator identifies when simultaneous transmissions from different entities in the system results in interference rendering the transmissions useless. These transmissions are dubbed collisions here.

The results show that the throughput of the system is greatly increased by limiting the amount of time a BS is active. For the case studied, the best system performance is obtained when each BS is active for quite a small fraction of the time ($< 40\%$). Another interesting finding in this work is that there is a significant discrepancy between the uplink and downlink performance: the downlink delivers better throughput due to the greater amount of overhead introduced by uplink overheads.

One issue that had a significant impact on the system performance was that of transmission of the broadcast information on the downlink. As all the BSs were synchronised and this information is transmitted at full power at the same point in a frame, this was frequently the cause of collisions. One way to mitigate this may be to consider how the system performs in asynchronous operation.

Acknowledgments

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