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The impact of MS velocity on the performance of frequency selective scheduling in IEEE 802.16e Mobile WiMAX.

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Abstract**—The OTA performance of Frequency Selective Scheduling (WiMAX Band AMC mode) is compared with that of Frequency Diverse Scheduling (WiMAX PUSC mode) as MS velocity is increased for Mobile WiMAX 802.16e. Frequency Selective Scheduling is shown to outperform Frequency Diverse Scheduling for velocities less than 15km/h and demonstrates upto 50% gain in throughput over the latter. The practical implications of this margin are: that pedestrian MSs in urban deployments may leverage the benefits of fast fading for performance gains without risk. And scheduler implementations can benefit from opportunistic switching between the two schemes given appropriate differentiating inputs.**

I. INTRODUCTION

Frequency selective scheduling uses BS (Base Station) estimates of MS (Mobile Station) channel conditions to approximate an optimal allocation of resources to users. It relies on reliable and timely estimates of channel conditions. Its performance is therefore commonly assumed to degrade as MS velocity is increased. The standard proposed alternative at high velocity is to use Frequency diverse scheduling, which spreads user resources over a large bandwidth so as average out the negative effects of frequency selective fading when it is no longer to possible to capitalize on it. We compare the two approaches in 802.16e as MS velocity is increased to determine a practical crossover point for differential scheduling strategies.

The rest of this paper is organized as follows: Section-II provides some background information, describes the two scheduling approaches, and motivates the case for the study expounded in this paper. Section-III describes prior related work. Section-IV details the technical aspects of the simulations performed, and Section-V presents the results. The results are discussed with relation to practical scheduler decisions in Section-VI and Section-VII concludes.

II. MOTIVATION

Conceptually, an OFDMA (Orthogonal Frequency Division Multiple Access) frame is a 2D grid of resource units. Each resource unit has a temporal and a subcarrier index, as illustrated in Figure-1.

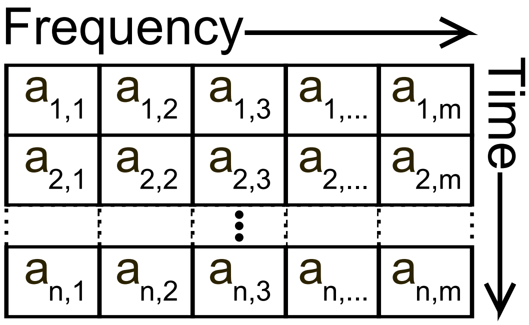

Fig. 1. The resource space provided by OFDMA is a grid indexed by frequency and time. Resource unit a_{ij} has temporal index i and subcarrier index j.

Each resource unit corresponds physically to a data symbol. A data symbol is a point on a constellation diagram of some MCS (Modulation and Coding Scheme)[1]. As an example, if QPSK (Quadrature Phase Shift Keying) is being used, then a symbol will take one of the values $\{00, 01, 10, 11\}$.

The scheduler at the BS is responsible for allocating resource units within a frame to MSs and for transmitting the frame. The path that the frame takes to the MS will contain obstacles which may be moving and which will absorb different wavelengths of EMR (Electromagnetic Radiation), the frame will be subject to other interfering transmissions, Doppler corruption, and reception of the frame will be compounded by multipath reflections.

These factors conspire to corrupt each data symbol in the frame individually in a way which depends on the position and motion of the receiving MS relative to the BS, and the exact time at which received frames are transmitted. Thus the

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[1] Note that 802.16e also uses the term “OFDMA symbol”. This refers to the combination of all symbols in one column and should not be confused.

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received power profile is said to be frequency selective and time dependent.

If it could be known in advance, for each MSs, how the channel would act upon each resource unit, then more intelligent choices could be made when allocating resource units to MSs. This is the motivation behind the scheduling technique known as Frequency Selective Scheduling.

Frequency Selective Scheduling acknowledges the frequency dependence of channel corruption and attempts to combat this by maintaining estimates for the channel conditions of each MS. These estimates, typically resource unit SINR (Signal to Interference + Noise Ratio), are constructed from information reported by MSs or from an assumption of reciprocal channel conditions. Scheduling decisions can then be made to give each MS the resource units that the BS estimates will be received with best SINR. The difference between BS estimates of channel conditions and actual MS experience mediates the success of the approach. Of the myriad factors which can affect the difference, this paper focuses on the affect of MS velocity.

When the velocity of an MS is increased, its conditions change more often, and thus measurement reports sent to the BS become increasingly innacurate with respect to the point at which they were taken. Eventually it no longer becomes profitable to use frequency selective scheduling. The usual antidote is to apply frequency diverse scheduling instead. In frequency diverse scheduling, MS resource units are spread evenly over the whole bandwidth available. The motivation behind this is as follows: if p is the probability that a resource unit selected at random will experience interference above some threshold required for proper reception, then p^N is the probability that N randomly chosen resource units will *all* be subject to such interference. So long as no two resource units are closer than the coherence bandwidth of the channel[1]. Thus, spreading has the effect of de-correlating the corruption experienced by resource units in a transmission block. This improves the average block error rate, at the expense of throughput.

These two approaches; frequency selective and frequency diverse scheduling are seen as alternative solutions to the problem of scheduling in traffic situations differentiated by the average velocity of MSs. The following question is hence posed:

At what velocity in an 802.16e network does MS throughput using frequency diverse scheduling exceed that of MS throughput using frequency selective scheduling? Or in other words, at what velocity is the optimal switch point?

III. PRIOR WORK

Three directly related works can be found in the literature. The first [2] is derived purely from theoretical considerations and provides scheduling strategy switchover values in the form of channel time-autocorrelations. The study, whilst interesting, is based on generic assumptions and provides the results in a form that do not directly nor easily map onto practical recommendations for 802.16e.

The second [3] is based on an accurate simulation of 802.16e at both the link and system level. Frequency Selective Scheduling cell average throughput is shown to exceed Frequency Diverse Scheduling at both 3km/h (by 18%) and 30km/h (by 5%), suggesting that Frequency Selective Scheduling may even be relevant for vehicular traffic classes. No faster velocity classes were tested, and it follows that further study is necessary to ascertain when, if at all the trend reverses.

The third paper [4] contradicts the second; a 50% performance gain for Frequency Selective Scheduling relative to Frequency Diverse Scheduling is demonstrated at a MS velocity of 3km/h, and yet at 8km/h Frequency Diverse Scheduling is demonstrated to outperform Frequency Selective Scheduling by 5%. It is not clear whether this discrepancy is due to error in either one of the last two studies, or from the confounding effects of the scheduler employed by the last, or just natural variance of the techniques under differing conditions.

Regardless, since neither of the practical studies provides bounded recommendations for 802.16e, and a contradictory state of affairs is the result, repetition of the study under conditions similar to [3] is warranted to euclidate the matter and is the subject and motivation for this paper.

IV. EXPERIMENTAL METHOD

A. *Scheduling in 802.16e*

The minimum resource block that can be constructed in 802.16e is called a slot and contains 48 data symbols. There are a number of ways to construct slots that differ in how resource units are drawn from those available. The slot types that are important here are PUSC (Partial Use of Subcarriers) and Band AMC (Band-Adapative Modulation and Coding).

In PUSC mode a slot spans 24 subcarriers and 2 time slots. Resource units are drawn according to a complicated two-stage permutation scheme which spreads them evenly over the entire bandwidth allocated to the sector. Any scheduler which employs PUSC is therefore called frequency diverse.

In Band AMC, slots are constructed from 6 bins. A bin contains 8 data subcarriers that are contiguous in frequency. Bins may be arranged in the following ways to form Band AMC slots: $\{1\text{x}6, 6\text{x}1, 3\text{x}2, \text{and } 2\text{x}3\}$. The notation $A\text{x}B$ means that the slot contains A bins next to each other in frequency, and B bins next to each other in time. Thus Band AMC slots are always constructed from bins which are next to each other in both time and frequency. A Band AMC slot contains 6 evenly distributed known pilot symbols from which the receiver can perform channel estimation.

A scheduler which takes advantage of the channel estimates that Band AMC offers for its contiguous slots, is called frequency selective[2].

B. *Link layer assumptions*

Link layer simulation assumptions are given in Table-I.

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[2] Note that in principle the scheduler could be preemptively time selective if it could accurately predict future channel conditions.

TABLE I
LINK LEVEL PARAMETERS

Index	Parameter	Value
1	Link direction	Downlink only
2	Carrier frequency	2.6 GHz
3	Bandwidth	10 MHz
4	NFFT size	1024
5	Frame length	5ms
6	Cyclic prefix length	1/8th
7	Forward Error Correction (FEC) type	CCTB
8	Slot type when Band AMC is used	2x3
9	Pilot boosting	2.5db
10	CCTB circulation depth	60
11	CCTB decision depth	60
12	Block height	6 Subchannels
13	Block width (Band AMC)	18 OFDMA Symbols
14	Block width (PUSC)	12 OFDMA Symbols
15	CQI feedback period	1 frame
16	Channel estimation assumption	Perfect
17	Channel type	Jakes, VecA
18	Number of transmit antennas	1
19	Number of receive antennas	1
20	MIMO	None
21	HARQ	Disabled

Parameter 1 indicates that the simulation is downlink only. Parameters 2 to 8 are taken from The WiMAX forum Mobile system profile, Release 1 [5], this is a restriction on the 802.16e parameter space that provides a standard to which manufactured devices must conform if they wish to be WiMAX Release 1 certified. Parameter 9 is as specified in the 802.16e standard [6].

Parameters 12, 13, and 14 define the size of the transmission burst to simulate. The rectangular frequency-time shapes for transmission bursts for Band AMC and PUSC in this implementation are different: a Band AMC block is 50% longer in time than a PUSC block (18 vs 12 OFDMA symbols), whereas a PUSC block takes up 50% more frequency spectrum than an Band AMC block (144 vs 108 subcarriers). This is because Band AMC and PUSC subchannels have lengths of respectively 3 and 2 OFDMA symbols and widths of respectively 18 and 24 subcarriers. Further, in order to use a repetition rate of 6 using our implementation the number of subchannels had to be a multiple of 6. For comparable throughput results however, the total number of resource elements in each type of burst needs to be equal. The settings here ensure this, giving a burst size of 36 slots.

The shape and size of a Band AMC burst is important because the decoder performance depends on how coherent the burst is with respect to deviations in SINR. In the absence of quantitative simulation results it is difficult to speculate on the optimality of the choice here with regard to each encoding type Band AMC and PUSC. And in fact such an optimality study could constitute an independent thread of research. Therefore the results should be considered with this in mind.

Parameters 15 and 16 specify optimistic feedback requirements and channel estimation assumptions. These were chosen to provide an upper estimate of performance.

Parameter 17 indicates that the channel used was Jakes ITU Vehicular A. This is a simple multi-tap channel where the delays and mean powers are taken from a known reference [7] to facilitate comparison with other results.

MIMO is disabled and no receiver diversity is used, as indicated in parameters 18,19,20, and 21.

Simulations were executed for the frame encoding types shown in Table-II:

TABLE II
DESCRIPTION OF LINK LEVEL PERMUTATION SCHEMES TESTED

Permutation scheme	Description
PUSC	PUSC encoded subchannels
BAMC 1	Band AMC with subchannels 1-6 always selected from an SINR ordered list sorted in descending order. (Best set)
BAMC 2	Band AMC with subchannels 7-12 always selected from an SINR ordered list sorted in descending order. (Second best set)
BAMC 3	Band AMC with subchannels 13-18 always selected from an SINR ordered list sorted in descending order. (Third best set)

The best set, second best set, and third best set Band AMC variations are intended to emulate the action of frequency selective scheduling to differing degrees of benefit. The PUSC variation is used to emulate the action of spreading.

The following velocities, given in km/h, were studied:
$\{1, 2, 3, 4, 5, 7, 10, 13, 15, 20, 25, 30, 40, 50,$
$60, 70, 80, 90, 100, 110, 120, 140, 160, 180, 200, 250, 300\}$

This range covers with finer granularity the ranges covered by both [4] and [3] and considerably extends the range of the latter in order to see how far the benefits of frequency selective scheduling extend.

The following MCS schemes were examined:
{ QPSK $\frac{1}{2}$ Repetition rate 6, QPSK $\frac{1}{2}$ Repetition rate 3, QPSK $\frac{1}{2}$, QPSK $\frac{3}{4}$, 16 QAM $\frac{1}{2}$, 16 QAM $\frac{3}{4}$, 64 QAM $\frac{2}{3}$, 64 QAM $\frac{3}{4}$ }

These MSC schemes were chosen to be the same as used in [3] in order to facilitate better comparison of results.

For each frame encoding, MCS, and velocity, SNR values between -20 and 30 in steps of 2dB were examined. For each SNR point, 300 blocks were simulated and the average PER (Packet Error Rate) recorded.

C. System level assumptions

From the link level results discussed in the last section, MCS curves were derived to use with the system level simulator.

A full list of parameters is given in Table-III. The system layout was 1 tier containing 21 cells with wrap-around for pathloss. Mobility of users was set according to the velocity examined. The range of velocities studied was the same for the link level case above. The scheduler used was simple Round Robin. The reason that this is acceptable, given that a frequency selective mode of operation was under test, is because the link level curves here already capture the effects of on average choosing the nth best set of subcarriers.

The site to site spacing ensures that coverage exceeds thermal noise and that the system is interference limited.

TABLE III
SYSTEM LEVEL SIMULATION PARAMETERS

Parameter	Value
Simulation duration	10000 frames
Link direction	Downlink only
CQI averaging window	4 frames
Fading granularity	10m
AMC threshold	10%
Site to site distance	1km
Sector count per site	3
MS per sector	25
HARQ	Disabled
Handover	Make before break
Traffic model	Full queue
Scheduler	RoundRobin
Reuse	1

V. RESULTS

Figure-2 shows the system level results for the full velocity ranges tested and Figure-3 shows the same results but magnified to show only the first 30km/h.

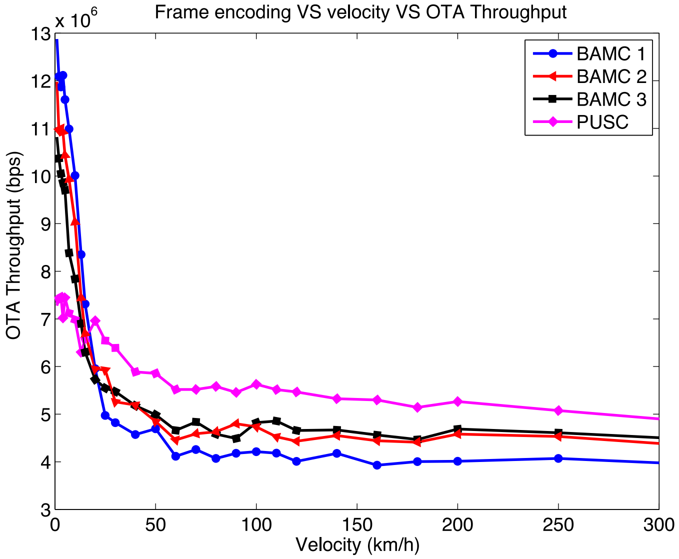

Fig. 2. System level performance results for the four permutation schemes tested, as a function of velocity.

At 1km/h the difference between AMC_1 and PUSC is very large, almost twice the over the air throughput (7Mbps vs 13Mbps).

The switchover occurs at approximately 15km/h. With reasonable confidence it can be claimed that there is still a benefit to be had at 10km/h.

VI. DISCUSSION

The results demonstrate that low velocity MSs can capitalize on Frequency Selective Scheduling.

A. Scheduling decisions

In some circumstances, such as airports and other large indoor structures, it should be possible to use frequency selective scheduling for all users. However, in many cases the traffic mix will contain both vehicular and pedestrian classes, and thus some means of choosing between frequency selective and frequency diverse scheduling should be constructed.

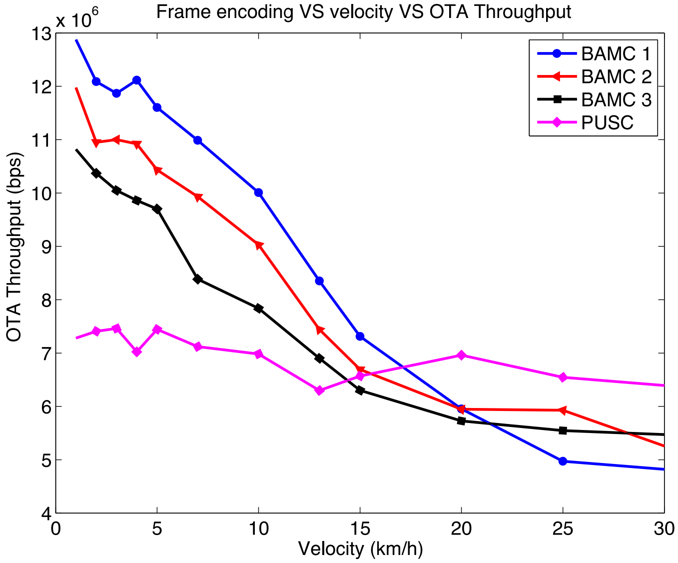

Fig. 3. System level performance results for the four permutation schemes tested, as a function of velocity. This plot only shows velocity upto 30km/h.

If all MSs were equipped with GPS receivers, velocity estimation outside would be accurate enough to use for switching. In principle only one bit would be needed for communication; indicating that the MS is traveling either less or greater equal than the switch point. Unfortunately, not all MSs are currently shipped with GPS receivers, so a different solution must be sought.

In [8] a MS positioning algorithm is constructed for 802.16e. The results presented indicate location accuracy to 250m and if the result is scaled down to an urban site spacing, the worst case accuracy reduces to about 5m. The paper says nothing of the variance from one measurement point to the next and thus nothing useful can be deduced about velocity prediction.

Perhaps a more readily implementable method for switching between scheduling approaches would be to test the throughput gained by each candidate for a short period. The scheduler could then decide accordingly. This would only be practical if the efficiency lost during testing could be recouped by the gain in switching. This implies that testing times would have to be short. Constructing a reliable means to switch between the two scheduling approaches is a future goal.

B. Sensitivity to parameters

It is worth reflecting on some of the implementation decisions made here, since it is likely that performance will exhibit sensitivity to them if they are changed. The following list contains the most salient:

1) Burst size and shape: Although 802.16e permits slots to be allocated individually to MSs, in practice the signaling overhead of doing so is prohibitive. There are few if any FEC methods that can operate within such a small space and so MSs are allocated in groups of slots called bursts. In the experiments described here, each burst contained 36 slots.

Burst size is a trade off: large bursts are more susceptible to interference than small bursts, but small bursts require more signaling overhead because the size and MS owner of each burst must be specified individually in the 802.16e DL-MAP. The relative performance gains attributed to Frequency Selective Scheduling at low velocity should increase as burst size is reduced until the associated overhead becomes dominating.

Burst shape is also important. A burst that has a long temporal duration but a narrow frequency spread will be more susceptible to temporal fading than it will frequency fading, and vice-versa.

As a final point, in LTE [9], the size of a slot (Resource Block in LTE teminology) is fixed to 12 subcarriers x 7 OFDMA symbols (6 in the extended prefix case), whereas Band AMC slot size in 802.16e is is one of $\{9\text{x}6, 6\text{x}9, 18\text{x}3, \text{or } 27\text{x}2\}$. Thus, there are differences in the sizes and shapes of burst that LTE and 802.16e can transmit. These subtle differences could manifest as differences in performance for the same scenario, depending on how close to the optimal burst size and shape each technology can realize.

2) Channel estimation accuracy: Frequency selective scheduling depends on accurate channel estimation. In the experiments performed here, channel estimation was considered to be ideal. This does not imply perfect reconstruction of transmitted symbols because there are noise sources such as thermal noise and inter-symbol interference which are non-invertible given channel estimation information. However it should be assumed that by employing ideal channel estimation, the results presented provide an upper bound on performance, since any degradation in channel estimation is likely to degrade performance. The effect of introducing imperfect channel estimation on the performance gains should be investigated.

3) CQI feedback delay: Frequency selective scheduling requires channel estimates that are fresh in the sense that they reflect the receiver MS experience. The time between updating these estimates, in the case that they are provided in the UL by the MSs, is known as the feedback delay.

In this work the feedback delay was one frame, which is the theoretically smallest feedback delay that 802.16e can realize. CQI estimates obtained from the DL portion of frame n are fed back in the UL portion of frame n and are available to the scheduler for frame $n+1$.

It may not be practical to feedback CQI information every frame and feeding back CQI information consumes uplink resources, impacting the overall data throughput. Further, it may be redundant to feedback CQI information every frame if it is changing infrequently. Thus it seems prudent that further work should investigate the positive impact on performance of increasing the feedback delay. A scheme such as in [4] where the feedback delay is dynamically adjusted could be employed.

It is worth noting that LTE allows CQI reporting and scheduling decisions to be made once per subframe (every ms) compared to every 5ms in 802.16e, so that LTE has a greater flexibility in this regard and hence frequency selective scheduling maybe more efficient in LTE.

4) Increasing the number of antennas: Adding additional antennas, gives a scheduler more choices for burst selection; a user who has poor conditions in one spatial dimension may gain better conditions in another. Increased choice in burst selection may reduce the likelihood of “decision collisions”, whereby two users with the same priority have the same preference for a band, forcing the scheduler to downgrade one of them. Future work should examine the notion of frequency-space selective scheduling.

More generally, increasing the bandwidth will increase the decision space of the scheduler and leads to the question as to whether frequency selective scheduling gains scale with bandwidth.

VII. CONCLUSION

Frequency selective scheduling is a viable means of increasing throughput in 802.16e and throughput can almost be doubled at low velocity under ideal conditions. The work here demonstrates that a frequency selective scheduling scheme such as the WiMAX Band AMC mode of operation should be selected for urban cells in which the traffic source is dominated by pedestrians or stationary users. In rural environments, in which a system is deployed specifically to serve roads or railways, a frequency interleaving approach such as the PUSC mode of operation should be selected. It remains to be seen what effect more realistic constraints will have on the performance. The impact of other contributing factors and their interactions should be the subject of future work.

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