Towards Systems Beyond 3G Based on Adaptive OFDMA Transmission

Wireless systems that assign different sets of frequencies to different terminals promise to provide high performance to meet the challenging requirements of future systems.

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ABSTRACT | High data rates, high spectral efficiency, flexibility, and low delays over the air interface will be important features in next-generation wireless systems. The overall challenge will be packet scheduling and adaptive radio transmission for multiple users, via multiple antennas and over frequency-selective wideband channels. This problem needs to be structured to obtain feasible solutions. The basic simplifying assumptions used here are clustering of antennas into cells, orthogonal transmission by use of cyclic-prefix orthogonal frequency-division multiplexing (OFDM) and a time-scale separation view of the total link adaptation, scheduling and intercell coordination problem.
Based on these assumptions, we survey techniques that adapt the transmission to the temporal, frequency, and spatial channel properties. We provide a systematic overview of the design problems, such as the dimensioning of the allocated time-frequency resources, the influence of duplexing schemes, adaptation control issues for downlinks and uplinks, timing issues, and their relation to the required performance of channel predictors. Specific design choices are illustrated by recent research within the Swedish Wireless IP program and the EU IST-WINNER project. The presented results indicate that high-performance adaptive OFDM transmission systems are indeed feasible, also for challenging scenarios that involve vehicular velocities, high carrier frequencies, and high bandwidths.

KEYWORDS | Broadband radio transmission; channel-aware scheduling; channel estimation; channel prediction; channel quality feedback; link adaptation; mobile radio systems; new air interfaces; orthogonal frequency-division multiple access (OFDMA); orthogonal frequency-division multiplexing (OFDM); scheduling; spatial division multiple access (SDMA); time-division multiple access (TDMA); wireless broadband

I. INTRODUCTION

Soon after the IMT-2000 standardization of third-generation (3G) wireless systems, the question arose what would come beyond. For some years, it seemed that by enabling the seamless cooperation of existing radio systems (like 3G and WiFi), the near-future market needs could be satisfied. This situation has now changed. The recent rapid increase in wireless data enabled terminals has increased the interest in improved air interfaces that offer performance competitive to that of wired broadband access. While delivery of high data rates in localized hot-spots is feasible [1], the most challenging problem is that of providing high data rates and simultaneously supporting good coverage and mobility [2]. The use of orthogonal frequency-division multiplexing (OFDM) was early identified as a promising technology [3] and it has several features useful for wireless broadband transmission.

- It enables flexible allocation of radio resources.
- It enables the use of orthogonal multiple access schemes that reduce interference within cells. In,

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e.g., code-division multiple-access (CDMA) uplinks, multiuser interference can be eliminated only by advanced receiver techniques.
- Due to low intersymbol interference, receiver processing becomes simple. In contrast, the length of channel impulse responses increases with an increasing sampling rate/data rate in conventional single-carrier transmission. Equalizer complexity then becomes an increasingly challenging problem [4].

Waveforms generated by OFDM do have high envelope variations which affects the power efficiency and economy of transmitters, but these problems can be reduced.

Increased data rates will require higher bandwidths and these can be found mainly at higher carrier frequencies. This effect results in deployments that use smaller cell sizes (see, e.g., [2, Fig. 3]), which are more expensive but also provide higher capacity per area. With large required bandwidths, it is important to use spectrum and transmit power efficiently. Here, adaptive transmission, in particular, in combination with multiantenna transmitters and receivers, offers powerful tools.

Classical transmit schemes presuppose little or no channel knowledge at the transmitter and they use diversity in various dimensions (time, frequency, polarization, and space) to reduce the unknown channel variability. *Adaptive transmission* instead uses channel knowledge to adjust the transmission. See, e.g., [5] and [6] for surveys of link adaptation.

Furthermore, channel information at the transmitter also enables *channel-aware scheduling* of transmission resources. We then not only adjust to the channel variability, we utilize it to improve performance. Different users will, in general, have different frequency-selective channels. Time, frequency, and spatial resources can then be allocated to the user who can use them best, or needs them most urgently. The resulting multiuser scheduling gain in throughput [7] grows with the number of competing users and with the variability of the channels. This scheduling gain may be considerably larger than the gain obtainable by link adaptation only.

In particular, *orthogonal frequency-division multiple access (OFDMA)* allocates different sets of frequencies to different terminals. This is a valuable improvement on scheduling only with respect to the time-variations of the received power, as is done in UMTS high-speed downlink packet access (HSDPA). The time variability is small for terminals at stationary locations. For mobile terminals, the channel gain variations between time-slots will decrease when the frequency extent of the time-slots is increased. The variability between frequencies will instead increase with a wider bandwidth, increasing the potential scheduling gain.

OFDM can now be considered mature as a basic technology and OFDM-based solutions were considered as alternatives for cellular wireless systems already during the 3G standardization effort. OFDM has been introduced in wireless local area network (WLAN) standards [8] and this technology is the primary alternative in newer wireless broadband standard proposals such as IEEE 802.16 WiMAX [9], [10] and WiBro [11]. An important development is the ongoing Third-Generation Partnership Project Long-Term Evolution (3GPP-LTE) or Evolved UTRA standardization effort [12], [13], where the use of adaptive OFDMA is proposed for the downlinks.

It is, therefore, now appropriate to try to summarize the design issues that are encountered when utilizing adaptive transmission in OFDMA-based systems beyond 3G. Here, we will not describe the evolving standards,[1] but rather focus on some of the challenges involved in any design that would have the following aims.

- Multiple data flows are transmitted over frequency-selective wide-band channels. Sets of infrastructure-connected antennas communicate with terminals that each may have multiple antennas.
- Packet data is to be transmitted flexibly and adaptively with respect to the properties and quality-of-service demands of the different packet flows.
- Time, frequency, and spatial (antenna) resources are to be scheduled and used adaptively with respect to the channel properties, whenever this improves the transmission.
- A low latency over the air interface is desired. This enables adaptivity with respect to fast channel variations, it facilitates high-throughput transmission control protocol/Internet protocol (TCP/IP) traffic and it enables fast link retransmission, which is of advantage for the performance perceived at higher layers.

Numerous design aspects and tradeoffs are then encountered. Here, we have chosen to introduce them gradually, in three steps. Chapter II first gives a brief outline of the assumed type of transmission system. Chapter III and Chapter IV then survey the most important design problems, issues and available choices. Finally, Chapter V illustrates key aspects by a set of case studies performed within the Swedish Wireless IP program[2] and in the EU WINNER projects [16].[3]

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[1] Detailed solutions to many issues discussed here can be expected to be left open to vendor-specific solutions in future standards.

[2] See [14] for an overview and, e.g., [15] for the assumed target system.

[3] The WINNER (2004–2005) and the WINNER II (2006–2007) integrated projects have the overall goal to develop and assess a single radio interface that covers a range of scenarios, from isolated hot spots to wide area cellular deployment, by using different modes of a common technology, handling up to 1 Gbit/s cell throughput over bandwidths up to 100 MHz. The medium access control [17] and a flexible multiantenna transmission framework [18], [19] are important for the aspects related to the present discussion. The WINNER projects also investigate the use of fixed relays, in particular, decode-and-forward layer two relay nodes [20] and flexible spectrum use/sharing.

Among others, the following problems will be addressed.

- What is the potential gain obtained by using the frequency variability of broadband channels?
- What are the appropriate sizes of the resource units that are allocated to different users?
- What is an adequate level of channel prediction accuracy and what terminal mobilities can be supported?
- How can link adaptation, multiantenna transmission, and multiuser scheduling be organized in a computationally efficient way?
- What air interface delays are realistically attainable, and what constraints do these place on computational delays and transmission control loop designs?

II. DESIGN AND SYSTEM ASSUMPTIONS

A. Design Assumptions

When increasing the numbers of antennas and users, the problem of globally optimizing and adapting the transmission system would quickly become infeasible, due to the control signaling overhead and computational complexity. Therefore, restrictions have to be imposed on the problem.

An efficient type of simplification is to subdivide the problem into subproblems that require limited mutual interactions. Such a subdivision can be performed in various ways with respect to the main dimensionalities encountered in our problem: space/antenna resources, radio frequencies, and time/timescales. Our discussion will aim at a feasible design based on the following simplifying assumptions.

Clustering of antenna resources. We define a *cell* as a region served by a set of backbone-connected antennas that can be coordinated to enable joint coherent transmission and reception. These constitute the (possibly spatially distributed) *base station* antennas of the cell. To control the complexity of the total solution, tight coordination between antenna elements of adjacent cells is not presupposed.

Use of orthogonal time-frequency transmission resources within cells, to control intracell interference.

Time-scale separation. The total problem is partitioned into subproblems that involve control and modification of different transmission parameters on different time-scales. Adaptation at a faster time-scale can then proceed with the parameters that change at a slower time-scale acting as semi-fixed constraints.

In particular, adaptive transmission will be regarded as a problem that needs the following mechanisms that naturally work at different time-scales.

- Transmission that adjusts to the small-scale and frequency-selective fading of the channel (time scale ≈ 2 ms). This scheme is denoted *frequency-adaptive transmission*. It places the highest demands on the control signaling, the channel measurements, and the feedback reporting. It also requires both fast adaptation control loops and the use of channel prediction to be feasible at vehicular velocities.
- Transmission that adjusts to the shadow fading and the long-term average interference power, but averages over the frequency-variability of the channel. This transmit scheme, here called *nonfrequency-adaptive transmission*, can be used as a safe fallback mode when frequency-adaptive transmission is infeasible. It is also appropriate for multicasting services, if several recipients of the service are within the same cell.

The distinction between frequency-adaptive and nonfrequency-adaptive schemes has also been proposed in [21]. If both of these schemes are used within the same cell, they need to share the total resource pool.

- *Resource division* preallocates the time-frequency-spatial transmission resources to be used for frequency-adaptive and for nonfrequency-adaptive transmission within a cell. It may adapt the allocation to the aggregate demands of packet flows, on a time-scale of tens of milliseconds.

Finally, intercell coordination would work on the longest time-scale.

- *Resource partitioning* defines the sharing of time-frequency-spatial transmission resources between cells, on time-scales of 0.1 s and above. Resource partitioning can be used to implement interference avoidance between cells and resource sharing between operators in a way that controls mutual interference [22].

B. Transmission Technology

The transmission within cells is thus assumed to be performed by (close to) orthogonal use of time and frequency resources. This requires the use of some form of multicarrier modulation or orthogonal time-frequency basis functions. Within the WINNER project, alternatives have been assessed, such as classical *cyclic prefix OFDM (CP-OFDM)* [23], IOTA basis functions that eliminate guard times [24], and PRP OFDM [25] that eliminates the need for pilots. The conclusion has been that CP-OFDM gives the best performance-complexity tradeoff [26]. In terminals, it is of interest to combine CP-OFDM with some type of discrete Fourier transform (DFT) precoding to reduces transmit signal envelope variations and the terminal cost [26]. CP-OFDM with and without DFT precoding can be seen as special cases of generalized multicarrier transmission (GMC) [27].

The design and evaluation examples in the following assume the use of coherent CP-OFDM transmission, possibly combined with DFT-precoded transmission from terminals.

C. Channel Symbols, Time-Frequency Bins, and Spatial Layers

With CP-OFDM, the smallest time-frequency resource unit is one subcarrier by one OFDM symbol duration, here denoted a *channel symbol*. Rectangular sets of n_s subcarriers by n_t OFDM symbols will be grouped into (time-frequency) *bins*.[4] The frequency-adaptive transmission will be assumed to use bins as its fundamental allocation units: A set of bins is then allocated to a packet flow, and individual link adaptation may be performed within each bin. This transmission scheme constitutes OFDMA with a TDMA (time division multiple access) component, and is denoted *TDMA/OFDMA* below. A bin will also be regarded as the smallest unit for performing the resource division and the resource partitioning.

If the base station has N_b antenna elements, then up to N_b spatial dimensions, here called *layers*, can be defined. A spatial layer within a bin will be called a *bin layer*. Some of the layers may be used for single-user multiple-input–multiple-output (MIMO) (multiplexing) transmission. Different spatial layers can also be used for transmission to/from multiple terminals, denoted spatial division multiple access (SDMA). While time and frequency can be treated as (approximately) orthogonal resources, this is unfortunately not the case for the spatial dimension.

D. Duplexing, Frames, and Slots

The transmission in downlinks (base station antennas to user terminals) and uplinks (terminals to base station antennas) needs to be organized with respect to time and frequency. One may use time-division duplexing (TDD), where the transmission switches between downlink and uplink periods in a predefined pattern within the whole utilized bandwidth. Alternatively, frequency-division duplex (FDD) may be used, where uplink and downlink transmission proceeds in separate frequency bands. Each of these schemes has both advantages and drawbacks, see [28] for a survey. In *half-duplex FDD*, which is used in, e.g., GSM, terminals use different bands for uplink and downlink. Their transmission/reception is also slotted in time as in TDD and they, therefore, do not transmit and receive simultaneously. This eliminates the need for duplexing filters in terminals, thus reducing their cost.

Here, we will follow the assumptions made in IEEE 802.16e [9] or in the WINNER project, in that either FDD or TDD may be used. For FDD, both full- and half-duplex terminals are to be supported.[5] In a TDD mode, there are time intervals denoted *frames* that consist of a downlink transmission *slot* and an uplink slot, separated by a small duplex guard-time. In an FDD mode, we likewise define a frame of fixed duration. It consists of two slots, each consisting of one or several bin durations. In the cell, one set of half-duplex terminals would receive in the first slot and transmit in the second slot. A second set of terminals could do the opposite. Full-duplex FDD terminals could transmit and receive in both slots, which doubles the maximal data rate.

E. Transmission Control Loops and Delay Targets

We assume that the resource allocation is controlled by the network, not by the terminals, since we thereby attain the highest spectral efficiency. Due to the assumptions introduced in Section II-A on tight coordination of all base station antennas and on time-scale separation, it will be possible to solve the scheduling problem for frequency-adaptive and nonfrequency-adaptive transmissions locally within each cell.

For each cell, a packet *scheduler* determines the allocations and link adaptations within the next slot. This requires interaction between the physical layer and the resource control, which is often placed in the MAC sublayer [11], [17], [29].

For downlinks, the scheduler allocates transmission resources within the next available slot to the active data flows. The allocation and the link adaptation parameters are reported to the user terminals over a separate downlink control channel.

In the uplink, a number of data flows that may originate in different user terminals are in competition for transmission resources. We here consider contention-free (scheduled) access, controlled by the base station. User terminals must then request uplink transmissions via an uplink control channel. The scheduler sends downlink control messages that specify the resource allocation and link adaptation. The transmission then proceeds over the indicated uplink slot. This procedure can be executed per slot, or by a longer term grant of resources at prespecified positions. The latter alternative would be useful for flows that generate fixed-size packets periodically.

A low delay over the air interface is one of our assumed basic design goals. The one-way delay is affected by the channel estimation/prediction computational delay, the scheduling computational delay, and also by the frame duration, which restricts the transmission timing. The retransmission delay is furthermore affected by the decoding delay.

There is a tradeoff between the attainable minimum delay over the air interface and the allowed computational delays. We will for our case studies use the following requirement.

- Downlink transmissions should be initiated and scheduled within one frame and be performed during the following frame. After reception, a retransmission delay of no more than one frame should be possible.

These are the minimal delays that can be attained in such a slotted transmission channel. The requirements imply that channel prediction, link adaptation/scheduling,

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[4] Bins are denoted chunks within WINNER and resource blocks within 3GPP LTE.

[5] FDD base stations can be assumed to use full duplex; the cost of duplex filters is of less importance here.

and decoding should each require at most half a slot (1/4 frame) delay.

We now survey the main problems involved when designing transmission schemes and resource allocation algorithms for frequency-adaptive and nonfrequency-adaptive transmission. We will also briefly discuss some of the tradeoffs involved in resource division and resource partitioning. The potential solutions will involve interaction between the physical layer, the medium-access control (MAC) sublayer and functions denoted radio resource management (RRM). We take a bottom-up approach here, starting with the physical layer.

III. PHYSICAL LAYER DESIGN ISSUES

A. OFDM Parameters and Bin Dimensioning

Let us begin by reviewing aspects that influence the dimensioning of the channel symbols and the time-frequency bins. The choice of cyclic-prefix OFDM parameters are mainly constrained by orthogonality and overhead considerations.

- A low intersymbol interference due to the channel delay spread and timing synchronization errors is desired. This requires a sufficient symbol guard interval (cyclic prefix).
- To limit the resulting overhead, the OFDM symbol duration should be considerably longer than the guard interval. An overhead below 15% is, in general, desired.
- However, a longer OFDM symbol time T_N results in a narrower subcarrier bandwidth $B_N = 1/T_N$. This increases the intercarrier interference-to-signal ratio due to synchronization errors and due to Doppler spreads.

An acceptable overhead and acceptable degradation of the orthogonality can, in general, be obtained. The most difficult tradeoffs occur if both long delay spreads and high velocities/Doppler spreads have to be accommodated by a design.

In general, the same link adaptation parameters can be used within neighboring subcarriers. This reduces the control overhead, which motivates the use of the bins introduced in Section II-C as allocation units. The constraint of equal link adaptation parameters within bins should result in an acceptable performance degradation, as compared with a case with flat-fading channel [30]. The bin width, therefore, depends on the smallest expected channel coherence bandwidth. The frequency selectivity of measured radio channels varies widely with the propagation environment. The variation of the received power with time and frequency is illustrated by Fig. 1 for one particular user and fading pattern. A statistical investigation of a large set of measured channels will be discussed in Section V-A1.

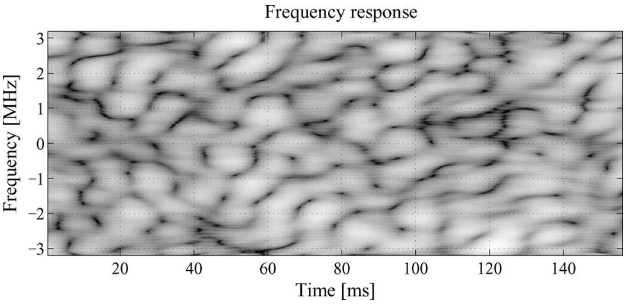

Fig. 1. ***Time-frequency representation of an estimated channel obtained from single-antenna measurement data on a 6.4 MHz channel at a 1880 MHz carrier. Light color denotes high received power. The dynamic range and the speed of the mobile is approximately 40 dB and 50 km/h, respectively. The coherence bandwidth is 0.6 MHz in this example.***

The appropriate bin duration is restricted by the time-variability of the channel. That, in turn, depends on the carrier frequency and the maximal supported terminal velocity [21]. Furthermore, a large bin could be too large for small packets.[6]

Furthermore, downlink control signaling that specifies the users of bins and the associated link adaptation parameters requires a fixed number of control bits per bin.[7] Smaller bins, therefore, result in larger downlink control overhead. If a fixed number of known pilot channel symbols are introduced within each bin to assist channel estimation, then smaller bins will also result in a larger pilot overhead.

Feedback reporting of bin channel quality predictions (Section III-B) could also result in larger overhead for smaller bins. However, such reports may be source coded [31], [32]. Source coded reporting overhead will be affected mainly by the channel correlation properties, not by the bin size.

The dimensioning of bins is exemplified in Section V-A2. Typical dimensions are bins of < 500 kHz × < 1 ms, that contain up to 500 channel symbols.

B. OFDM Channel Estimation and Prediction

OFDM channels are modeled by one time-varying complex coefficient per subcarrier. The channel variations are correlated between the subcarriers, with a smaller channel delay spread leading to higher correlation (and larger coherence bandwidth).

Channel estimation is required for two purposes.

- *Coherent reception* of payload and control data. Here, the research focus is on pilot-based methods that provide a first estimate [33]–[35], while

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[6] This type of inefficiency is denoted padding loss. Flow multiplexing, i.e., letting bits of different flows to/from the same terminal share a set of bins, is one tool for reducing the padding loss.

[7] For example, within the WINNER project, frequency-adaptive transmission control systems have been designed that require six downlink control bits per individually allocated bin.

iterative channel estimation and decoding of the payload data (turbo processing) can improve the estimates, if needed.

- *Channel prediction* to support channel-aware scheduling, as will be described in Section V-B. OFDM channel prediction can be performed either in the time domain [36], [37] or in the frequency-domain [38]–[40]. See [41] and [42] for surveys.

Frequency-adaptive transmission requires prediction estimates of the signal-to-interference and noise ratio (SINR) at one or several locations within each potentially useful bin. The SINR measurements and their accuracy estimates then have to be converted to a metric that determines the link adaptation parameters (choice of modulation, power and code rate).

Channel estimation and prediction errors will affect the link adaptation performance, see [43] for a survey. For an assumed prediction error pdf, the modulation and code rate limits can be adjusted to retain a target bit error probability, see [44] or [6, Sec. IV]. One may alternatively maximize the throughput [45]. Prediction quality adequate for scheduling and link adaptation is obtained over prediction horizons in time that correspond to roughly 1/3 wavelength in space [31], [46]. This is an important factor for scaling the feedback loops and frame durations, see Section V-B. Beyond the predictability limits, diversity-based techniques (nonfrequency-adaptive transmission and space–time coding) must be used [47].

SINR prediction requires prediction of both the channel power gain and of the noise plus interference power. The least interference predictability, for a known average interference power, is represented by a white Gaussian assumption.

The use of FDD or TDD affects the channel predictor design. In TDD, we may use the channel reciprocity between downlink and uplink to estimate the channel of a link based on measurements of the opposite link. This holds for calibrated single antenna- and multiantenna systems, if the frame is much shorter than the channel coherence time.[8] Such designs are not possible in FDD.

Of the eight possible combinations of FDD/TDD, uplink/downlink and frequency-adaptive/nonfrequency-adaptive transmission, the case of frequency-adaptive transmission in FDD uplinks represents the most challenging prediction problem. Due to the use of different and widely spaced carrier frequencies for the uplink and the downlink in FDD, channel reciprocity does not hold. Therefore, the uplink channel quality within *all* potentially useful bin layers, for channels from *all* terminals that are in competition for the uplink, have to be predicted at the base station (network) side, based on uplink pilots transmitted by all these terminals. This might easily lead to problems with the total uplink pilot overhead if many active terminals are involved. To reduce this overhead problem, channel predictors can use uplink pilots that are placed in overlapping (superposed) positions [39], [49]. This method has been used in the case study of Section V-B.

The *reporting overhead* can become excessive for prediction reports transmitted over the uplink from multiple users. Efficient compression techniques exist that use source coding over frequency samples and subsampling in time. Such methods reduce the overhead to quite acceptable proportions. Around 0.25 bits reported per user per scalar predicted bin layer quality are obtained at realistic terminal velocities, see [31] and [32]. Reports can furthermore be generated only when bursty packet-data flows need them [50].

An alternative technique that has been proposed is to signal an indicator of one or a few bits only for the bins whose predicted SINR is above a threshold [51]–[54].[9] It should be noted here that misleading estimates of the overhead are easily obtained if protocol aspects of the feedback channel are not taken into account [56].

For MIMO schemes that require feedback of the whole channel gain matrix, the appropriate use of limited feedback is an active research area, see, e.g., [57]–[61].

C. Link Adaptation

Link adaptation would be performed differently in the two considered transmission schemes.

- In frequency-adaptive transmission, payload bits from flows are allocated to time-frequency bins, or to one or several spatial layers of bins for multiantenna transmitters. Individual link adaptation may be performed here within each bin and layer, adjusted to the SINR.
- In nonfrequency-adaptive transmission, the frequency variations of the channels are reduced by averaging. Here, a code block is interleaved and mapped onto transmission resources within a wide frequency range. The same link adaptation is used within the whole code block. It is adjusted to the shadow fading and path loss, but not to the frequency-selective (small-scale) fading.

As mentioned in Section II-A, these schemes could be used by different sets of flows within one system and cell, sharing the set of transmission resources, as illustrated by Fig. 2.

1) Combining Coding and Link Adaptation for Frequency-Adaptive Transmission: There are several possibilities here. The simplest alternative is that we may schedule the bins that are best for a particular user, but not adapt the modulation per bin. Coded sequences are then mapped onto the allocated multiple bins, using one modulation format. This scheme is under consideration for the 3GPP-LTE downlink. The multiuser scheduling gains would then

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[8] However, the interference power at the far-end receiver can, in general, *not* be inferred from measurements by the near-end receiver [48].

[9] Unfortunately, the throughput resulting from this method can become extremely sensitive to the threshold setting, as observed in [55, Ch. 6].

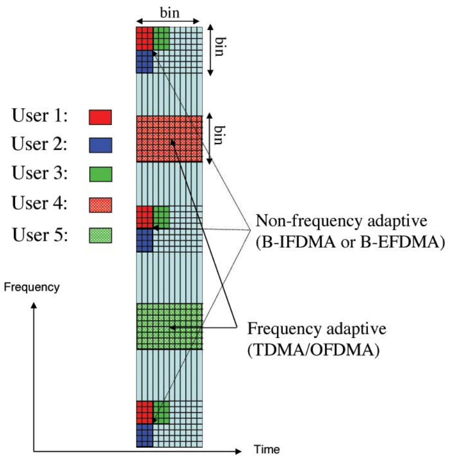

Fig. 2. ***Example of time-frequency resource division. Bins that are to be used for frequency-adaptive and nonfrequency-adaptive transmission are interspersed in the frequency direction of a slot. The indicated transmissions are all either downlink or uplink. The figure illustrates an example that uses WINNER [70] nonfrequency-adaptive multiple access schemes, denoted B-EFDMA in downlinks and B-IFDMA in uplinks. The transmission to/from each user terminal is then allocated exclusively to sets of small blocks (parts of bins.) These blocks are regularly spaced in frequency [71].***

be harnessed, but the constant link adaptation reduces the performance [62].

If we instead consider binwise link adaptation, the simplest alternative would be uncoded adaptive M-quadrature amplitude modulation (QAM) [5], [6]. It will be used in some illustrations in Section V-A. Better performance and a finer granularity of the rate matching is obtained by using coding, with bin-wise adaptation of the code and modulation rate, using one code block per bin. Since a bin will typically contain rather few channel symbols, the use of convolutional codes is then appropriate. Results from [31] and [46] that use this scheme are discussed in Section V-B5.

To obtain higher coding gains, one may finally use large code blocks encoded by strong codes, and map them onto several bins in which binwise link adaptation is used. This method promises to provide the highest performance. It has recently been proposed and investigated [63]–[65] and it will be discussed in Section V-B6.

2) Nonfrequency-Adaptive Transmission: When using an averaging strategy with respect to the frequency-variations of a broadband channel, turbo or LDPC codes are preferably used for larger packets [66]. To harness adequate frequency diversity, it is important to map also small code blocks onto resource units that are widely dispersed in frequency. Space-frequency coding enables the use of additional spatial and polarization diversity.

Possible ways to attain large frequency diversity is by frequency hopping [67] or by spreading, using multicarrier CDMA [23], [68]. Investigations within WINNER have found multicarrier CDMA to provide only small gains as compared with orthogonal allocation on frequency-dispersed time-frequency resource blocks [26], [69]. The current WINNER baseline design maps the code blocks to/from different users onto small rectangular time-frequency blocks (sub-bins), that are regularly spaced in frequency [70], [71], see Fig. 2. Orthogonal transmission simplifies the receivers. Use of small blocks increases the frequency diversity relative to allocation of whole bins. The regular spacing reduces the addressing overhead. It also enables the use of DFT-precoded uplink transmission which lowers the signal envelope variation. A short block duration enables terminals to be active only during short intervals, thus reducing their power consumption. It furthermore reduces the performance loss due to channel time variations within blocks, in particular, in very high velocity scenarios, such as for high-speed trains.

3) Link Adaptation in "Single-Carrier" GMC Uplinks: Use of GMC to produce single-carrier waveforms with a cyclic prefix is a technology proposed for 3GPP-LTE uplinks. A TDMA allocation would then be used, with the same link adaptation parameters within the whole utilized subband. If the subband is significantly wider than the channel coherence bandwidth, the fading within different parts of the subband will average out. This will reduce the attainable multiuser scheduling gain. Investigations in [72] indicate a large reduction of the multiuser scheduling gain when using single-carrier TDMA transmission on a 5 MHz bandwidth, as compared with using OFDMA. Comparisons of TDMA allocation versus OFDMA will be discussed in Sections V-A and V-B5.

IV. MAC AND RRM DESIGN ISSUES

A. Combined Link Adaptation and Scheduling

1) Separation of Link Adaptation and Scheduling for Frequency-Adaptive Downlink Transmission: Optimization of the scheduling, link adaptation and the multiantenna allocation are coupled problems, that may very well be unsolvable under the timing constraints introduced above. Let us begin by introducing two simplifying assumptions that lead to a significant reduction of the downlink design complexity.

- *Equal transmit power spectral density* is used in all bins that are allocated to one terminal.
- Bins are *exclusively allocated to terminals* in frequency-adaptive transmission.

If orthogonal resources (time and frequency) are assigned under the two conditions stated above, then the downlink allocation problem can be solved quickly and without iterations: A preliminary (hypothetical) single-user link adaptation can first be performed for each potential user of each bin. It determines the potential transmission rate to each user in each bin. Channel adaptive multiuser scheduling (Section IV-B2) then assigns at most one terminal to each bin.

Such a scheme could be executed well within the computational delay that would correspond to half a slot. It can be applied to all single-antenna or multiantenna downlink transmissions in which each bin is exclusively allocated to one terminal. Multiantenna transmissions may use beamforming and MIMO transmissions may use spatial multiplexing. Restricting link adaptation to use constant power above an adequate SINR reduces the capacity very little, as compared with the capacity-optimal (Hughes–Hartogs) power allocation law [65], [73].

For single-antenna transmitters, exclusive allocation of orthogonal time-frequency resources to the users with the highest SINR is known to achieve the sum capacity in Gaussian broadcast channels (downlinks) [74], if no delay constraints are placed on the scheduling. With delay constraints, the resource pool within a slot must be large and fine-grained enough (the bins small enough) so that all delay-constrained flows that need immediate access can be provided access.

For multiantenna transmitters, the exclusive allocation constraint would exclude the use of SDMA. This would lead to performance losses, in particular, when allocating terminals with low SINRs [19].[10]

Optimizing an allocation that allows the use of SDMA becomes more complicated [75]. Flows to/from different users would then share bins, by using different spatial layers. The resulting total interference experienced by one user then depends on which users are allocated to other layers. The required link adaptation parameters, therefore, depend on the outcome of the scheduling. It is theoretically possible to avoid such interference by coordinated transmitter-receiver beamforming [76], but spatial channels cannot in practice be fully orthogonalized without a careful selection (user grouping) of the users that are to share time-frequency resources by SDMA [77], [78].

An optimal SDMA solution, therefore, requires high computational complexity, but simple and efficient solutions can still be constructed. A key step is to perform an initial *spatial user grouping*. The aim is to identify users that create low mutual interference [18]. User grouping can be performed over an interval much longer than the frame, by utilizing long-term channel state information such as cross correlations, which change more slowly than the small-scale fading.

Multiuser scheduling can then be performed under the restriction that only spatially well separated users are allowed to use spatial layers within the same bin. This limits the interlayer interference. It is then possible to determine the link adaptation for each allowed user of each bin layer based on an assumed user-specific bound on this interference, and then perform the scheduling.

Spatial user grouping is adopted for SDMA assessment in the WINNER project [19], [26], using a fixed grid of beams as the baseline multiantenna transmit scheme. Adaptive beamforming is an alternative; see [78]–[80] for example algorithms. Multiuser receivers can furthermore be used to suppress the remaining interlayer interference [78].

2) Scheduling, Link Adaptation, and Fast Power Control in Uplinks: For multiple access channels (uplinks), the sum rate is highest when all users can transmit at full power. The maximal sum rate is then attained by FDMA with multiuser waterfilling power allocation [81]–[83]. This situation is more complicated than for the downlinks discussed in Section IV-A1. Under per-user power constraints, the transmit power per bin will depend on the number of allocated bins. The link adaptation will, therefore, depend on the scheduling; The number of bits that can be placed in a bin by a user can not be precalculated, like in Section IV-A1. The development of practical low-complexity solutions for realistically formulated uplink link adaptation and scheduling problems remains an important research problem [84].

3) Slow Power Control in Uplinks: The appropriate choice of slow power control that adjusts the *average* transmit power for uplink data channels is an interesting open problem.

The received SINR and, thus, the total uplink throughput and network capacity would be maximized by allowing all terminals to transmit with full power [85]. However, the terminal is often energy limited by its energy source, typically a battery, so power efficiency techniques are important. Furthermore, the base station has a finite dynamic range in its receiver and the digital baseband implementation relies on a finite number of quantization levels. In addition, due to, e.g., Doppler spread and imperfect frequency synchronization, transmissions from different users will not be perfectly orthogonal. In the spatial domain, we may have other user interference from other spatial layers.

For the above reasons, it is expected that there should be an upper limit on the allowed difference in received power spectral density from different users. Its purpose would be to limit various types of interference primarily from users with strong received signals. The limitation would require slow power control that follows the path loss and shadow fading. For example, the users might be allowed to chose their own transmit power levels as long as the received power spectral density is within an n dB window. Outside of that window, the base-station directed slow power control takes over.

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[10] Such users can most easily share bins with others, since the interlayer interference that would be introduced by SDMA will affect users less if they already experience high noise levels and/or intercell interference.

B. Scheduling Criteria and Constraints

Algorithms for the scheduling have a large influence on the system performance. Let us briefly discuss some aspects.

A packet *flow* is a transmission defined by sender, receiver, and a set of quality-of-service parameters. Several flows may be associated with one terminal. The scheduler controls the flows. It is assumed to be located on the network side and it controls uplinks as well as downlinks.

Flows can be controlled individually and we may assume per-flow queueing of packets, as illustrated by Fig. 3. The scheduling should have the overall aim of satisfying quality-of-service constraints for each flow [86], [87]. By channel-aware scheduling, it can also allocate advantageous frequency and spatial resources to the flows, to optimize the network capacity or the terminal power consumption.

Multiuser scheduling algorithms should not have high computational complexity, since the whole sequences outlined in Section IV-A1 should execute in less than half a slot. With slot durations of 0.3–0.6 ms as exemplified in Section V, this corresponds to $1.5 * 10^5$ to $3 * 10^6$ operations for a processor with a capacity in the range 1–$10 * 10^9$ ops/s.

1) Fairness Constraints Versus a Satisfied User Criterion: Fairness between users is a concept that has received considerable interest. In fixed networks, generalized processor sharing [88] is often used as a fairness benchmark. It states that each user should obtain at least its guaranteed share of the total service rate, a formulation that does not take user channel quality variations into account. A criterion more appropriate for channel-aware schedulers has been proposed in [89].

However, users have no knowledge of other users allocations and thus have no notion of fairness. The problem of allocating transmission resources to flows is basically an economic optimization problem, where fairness is, at most, an intermediate variable [90]. A useful way of capturing the overall aims is to instead define a *satisfied-user criterion*. Such a criterion is based on the following assumptions.

- Users (flows) that attain certain quality of service parameters (that differ between users) are considered satisfied. It is of no direct economic benefit to over provide a user with resources once these parameters are fulfilled.
- A given maximum percentage of unsatisfied users within the coverage area is accepted.

Simulation experiments are then performed where the number of users in the system/cell is gradually increased. The maximum number of satisfied users is obtained at the point where the percentage of unsatisfied users reaches its allowed limit.[11]

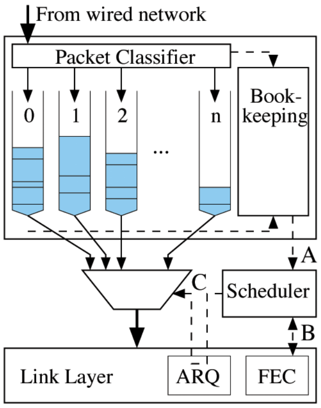

Fig. 3. ***Downlink buffer and scheduler. Packets are distinguished by flow and may be inserted into flow-specific queues. The buffer submits a status report (A) to the scheduler, containing information about the priorities, queue length and required link services. The scheduling decision (C) would typically give high priority to urgent time-critical packets of delay-sensitive flows and to retransmissions of erroneous segments (link-layer ARQ).***

We may then compare the maximum number of satisfied users within a coverage area that can be attained by different solutions. This allows different antenna resource allocation strategies, scheduling criteria, algorithms, and constraints (e.g. on fairness) to be compared and evaluated in a rational way.

2) A Brief Survey of Algorithms: In an idealized case where all users have queues that never empty, scheduling for maximal cell throughput becomes very simple. Each transmission resource is then given to the user with the highest predicted SINR. This "*max rate scheduling*" would starve users with low average SINR, although constraints can be introduced to alleviate this effect [91]. The *proportional fair* algorithm was designed to overcome this drawback, by weighting the allocation by the average attained data rates [92], [93] or, alternatively, by the average user SINRs. The latter variant is also denoted normalized carrier to noise scheduling [94]. The proportional fair algorithm and its variants tends to favor users with large channel variability. Schemes that normalize with respect to the channel statistics are the score-based algorithm [95], various pdf/cdf-based methods [90], [96], or schemes that allocate prespecified fractions of the resources [97].

In more realistic problem formulations, the queue levels and quality of service constraints must be taken into account. Algorithms have been proposed for serving flows with packet delay constraints [98], [99], or minimum rate requirements [100]–[104], while preserving some multiuser scheduling gains. Versatile algorithms can be based on criteria that combine queue lengths, bin capacities, and flow priorities [90], [105], [106]. The most challenging scheduling design and tuning problems occur in mixed

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[11] This percentage could be modified based on a further tradeoff between income loss versus infrastructure cost.

service environments, with flows with differing rate and quality-of-service requirements [107]–[110].

It should finally be noted that scheduling can only solve the resource allocation problem up to a capacity limit. When the demand is increased, queues will eventually start to overflow. The scheduler must, therefore, be integrated into a larger design that involves admission control [111]–[113], congestion control (including load rebalancing and resource repartitioning), and handover.

C. Resource Division

A packet transmission system may use frequency-adaptive transmission for some flows while it needs to use nonfrequency-adaptive transmission for others. The aggregate demand for the two types of transmission would vary with time. We assume that a resource division function adjusts these resource pools. This allocation should provide a semi-static environment for the schedulers but still be modified fast enough to react to changes in aggregate demand for these two types of traffic. It is convenient to define a time-frequency-spatial resource unit of longer duration, a *super-frame*, in which the resource division and partitioning remains fixed.

Both frequency-adaptive and nonfrequency-adaptive transmission require frequency diversity: The former utilizes it to obtain scheduling gains. For the latter, it represents a readily available dimension in which to obtain diversity in broadband systems. The resources allocated to each scheme should, therefore, preferably be allowed to sample a large part of the available bandwidth. Interleaving them in frequency is exemplified in Fig. 2 above. An alternative is to separate the two sets in time, e.g., by using one in each second frame. This would add delays and increase the required prediction horizons. Such time-multiplexing might be useful in low bandwidth scenarios, in particular, for single-hop deployments where a low delay can still be maintained and at low carrier frequencies where channel predictability is improved.

D. Resource Partitioning and Slow interCell Coordination

When all frequencies are available in all cells, (frequency reuse 1), the average downlink SIR (signal-to-interference power ratio) at cell edges will be low at high traffic loads, around −3 dB at full load for omnidirectional transmissions. Link adaptation and MIMO multiplexing work best at higher SIRs. The area spectral efficiency (bits/s/Hz/cell) might be increased by excluding some resources from use in each cell, if the improved link efficiencies due to higher SIRs outweigh the reduced resource pool available within each cell.[12] Frequency partitioning in cellular networks has received much interest [115], using power control [116], dynamic channel assignment, and channel borrowing.

However, channel-aware scheduling and bursty packet traffic complicate intercell interference avoidance. For example, it would not, without additional side information, be possible to conclude that the interference power in a set of subcarriers is likely to be higher/lower than average just because it is measured as high/low at present. This is a major challenge for dynamic measurement-based resource assignment schemes. The use of joint fast intercell power control and scheduling [85] is, therefore, problematic.

These problems are reduced by predefining sets of resources (guard bins) that stay fixed over a longer time interval, in which neighboring cells are not allowed to transmit. Such restrictions may apply only to specific directions/beams. One may envision such a slow intercell coordination to adapt on a time-scale of hundreds of milliseconds. See, e.g., [117] for an example scheme.

The purpose of such a coordination has to be clearly stated, just as in the case of scheduling design. Spectral efficiency at full load and maximizing the number of satisfied users remains important, but cellular systems will frequently operate at partial loads. To maximize the spectral efficiency of individual transmissions within a not fully loaded cellular system would simply result in additional unused resources. The economic advantage of doing so is unclear from a service providers perspective. The design metric for nonfully loaded systems might instead focus on user-centric parameters like terminal power consumption and/or data download/upload times.

Use of interference-protected resources provides the largest benefit when used in links that would otherwise have low SINRs at reuse 1 (typically for terminals close to the cell edge). A simple scheme allocates such low-SINR users to a separate frequency pool with, e.g., frequency reuse 3 [118]. This static fractional frequency reuse partitioning will be used in Section V-A3. Its effect on the maximal cell throughput depends on the interference level, the path loss and on the utilized multiantenna transmission scheme. A static fractional frequency reuse scheme improves throughput for single-antenna transmission systems operating at high cell loads [115]. The advantage in combination with e.g fixed grid-of-beam beamforming is less clear. At lower loads, we might attain higher peak data rates or lower delays by dynamic bin assignment [119] or by coordinated beamforming [4].

V. CASE STUDIES

In this section we review investigations within the wireless IP (WIP) [14] and WINNER [16] projects that are related to the design issues discussed above. We here focus mainly on frequency-adaptive transmission.

The WIP example design illustrates an adaptive OFDMA downlink based on FDD, for 3G-like bandwidths

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[12] Theoretically, large gains could also be obtained by coherent intercell signal combining [114], but this would require fast and tight intercell coordination and fast routing of data packets to/from many different sites in the network. We have here in Section II-A already defined a "cell" by the set of antennas for which tight multiantenna coordination is feasible.

of 5 MHz at 2 GHz carrier. In the WIP context, we motivate frequency-adaptive transmission based on channel measurements and discuss bin dimensioning. We indicate the resulting performance when using a multicell partial frequency reuse strategy, and also illustrate the effect of multiantenna diversity combining. Then, we discuss the impact of frequency offsets in the uplink and conclude with an example of interactions with higher layers—using the TCP protocol.

In the WINNER context, the design has been developed in more detail and the evaluation is taken further. The example design is for higher bandwidths and more challenging higher carrier frequencies. FDD uplinks as well as TDD downlinks and uplinks are included. We here discuss the adaptation control loops in more detail. We then evaluate the influence of channel prediction accuracy and investigate combinations of scheduling, coding, and link adaptation.

A. WIP Project Design and Investigations

The OFDM radio interface outlined below is used as a baseline design within the WIP project.

In Table 1, the design is exemplified for wideband code-division multiple-access (WCDMA) type of channels, dimensioned for delay spreads corresponding to up to 3 km distance and vehicle speeds up to 100 km/h. The bin size in Table 1 and Fig. 4 is appropriate for stationary and vehicular users in urban or suburban environments. It represents a reasonable balance between the spectral efficiency and the required control bandwidth, as discussed in Section V-A2. Here, a frame will equal two bin durations.

In frequency-adaptive downlinks, all active users must estimate the channel within the whole bandwidth. Out of the 120 channel symbols in a bin, 12 are allocated for pilots and downlink control, as shown in Fig. 4, leaving 108 payload symbols. The pilot and control symbols use 4-QAM and they can be detected within the whole cell. They are transmitted in all bins, also bins without payload data.

1) Frequency Variability of Measured Channels and the Potential Benefit of Frequency-Adaptive Transmission: Consider a user who is given the $x\%$ resources with highest power, i.e., the $x\%$ best timeslots in a TDMA system or the $x\%$ best bins in a TDMA/OFDMA system. For a given channel, we then compare the average received power of allocated bins for a TDMA and a TDMA/OFDMA type of allocation.

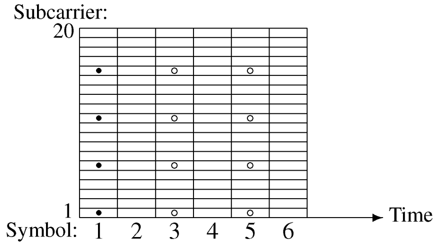

Fig. 4. ***Illustration of the WIP bin structure, containing 20 subcarriers with 6 symbols each, on 200 kHz × 0.666 ms. Known 4-QAM pilot symbols (black) and 4-QAM downlink control symbols (rings) are placed on four pilot subcarriers. The modulation format for the other (payload) symbols is adjusted adaptively. All payload symbols within a bin use the same modulation format.***

TABLE 1 Basic Parameters for Wireless IP FDD Wide-Area Scenario

Parameter	Full duplex FDD
Center frequency	1900 [MHz]
Number of subcarriers	512
FFT BW	5.12 [MHz]
Signal BW	2 x 5 [MHz], paired
Number of used subcarriers	500
Subcarrier spacing	10 [kHz]
OFDM symbol length (excl. CP)	100 [μs]
Cyclic prefix (CP)	11 [μs]
Physical bin size	200 x 666 [kHz x μs]
Bin size in channel symbols (subcarriers x OFDM symb.)	20 x 6 = 120

This is investigated for the system of Table 1, using measured channels obtained by channel sounding for 80 different urban and suburban environments.[13] The measurements use 6.4 MHz bandwidth centered at a 1880 MHz carrier frequency. Distances range 200–2000 m from the base station on a high building. Vehicle speeds are 20–90 km/h. For each of the 80 channels, 1430 noise reduced estimated impulse responses were calculated, based on 156.4 ms long measurements with channel sampling rate 9.1 kHz. Fig. 1 shows one of the estimated channels.

As shown in Fig. 5, a significant gain is obtained by frequency-adaptive allocation. This holds also for the channels that have rather high coherence bandwidths. Note that the coherence bandwidth influences, but does not fully determine, the attainable gain. From these results, an average gain of 3 dB SNR seems attainable in the measured urban and suburban channels. Power gains of more than 2 dB seem attainable also at high (2–6 MHz) coherence bandwidths. For larger total system bandwidths, we can expect larger gains.

2) Bin Dimensioning: The multiuser scheduling gain will be illustrated by figures such as Fig. 6, where the cell throughput increases with the number of competing users K, who each obtain on average the best fraction $1/K$ of the resources by maximum throughput or proportional fair scheduling.

Using such graphs, the choice of an appropriate number of subcarriers per bin is illustrated here by a result from [30]. (For investigations with this purpose, see also, e.g., [21].)

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[13] We thank Ericsson Research for providing these measurements.

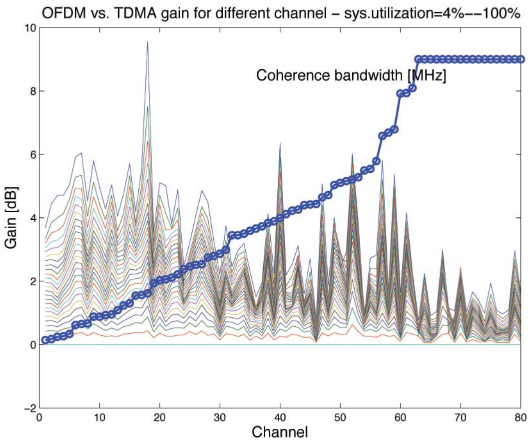

Fig. 5. ***Improvement (gain) of the average received power in dB, when using TDMA/OFDMA allocation instead of TDMA. Starting from above, a user is allocated the 4%, 8%, . . ., 100% best resources. The gain decreases toward zero for high system utilization, where the two schemes coincide. The channels are ordered according to increasing coherence bandwidth. The coherence bandwidth for each channel is also plotted separately as blue rings. For that plot, the left-hand axis is scaled in MHz. (Coherence bandwidths that are larger than the measured bandwidth 6.4 MHz are extrapolated estimates.)***

A single modulation format is used within bins. The variability of the channel within bins results in a loss in spectral efficiency as compared with a case with time-invariant additive white Gaussian noise (AWGN) channels within bins. With increasing bin width, this effect increases. Fig. 6 shows results for double bin size using 240 channel symbols (30 subc. × 8 symb.) and for half bin size of 60 (15 × 4), as compared with 120 channel symbols used in Table 1. Other relevant parameters are as in Table 1.

Halving the bin size leads to a somewhat higher spectral efficiency for the investigated channel, but would increase the control and pilot overhead from 12/120 to 12/60. Doubling the bin size somewhat reduces the spectral efficiency, but lowers the overhead to 12/240. These effects almost cancel for this investigated channel. The intermediate 120-symbol bin size used in Table 1 seems rather well balanced.

3) Performance in an Interference-Limited Environment: We now apply adaptive downlink transmission in a multicell context, using the system presented above. The nominal frequency reuse factor is 1 in the system, but a fractional frequency reuse strategy, so-called reuse partitioning (RUP) [118] is used. This improves the spectral efficiency at full load when using omnidirectional transmission within sectors (cells). In [15], the performance with RUP for sites with six 60° sectors/cells is investigated under the following assumptions.

1) Each sector is divided into an inner zone 1, which is allocated a fraction of the bandwidth and an outer zone 2, with the remaining bandwidth. The zone 1 band is used at all sites. To reduce interference from neighboring sites within the outer zone 2, its band is shared among sites in a classical reuse 3 pattern.
2) The scheduling for sectors belonging to the same site is coordinated by preventing simultaneous transmission to users close to sector edges. The power is also boosted by 3 dB in bins intended for terminals at sector edges, to counter the reduced antenna gain at the beam edge.

The sector throughput under the strategy above has been evaluated in an interference-limited environment, where the noise is neglected. This makes the results invariant to absolute power and distance scales. The path loss and the small-scale fading modeled as Rayleigh-fading is considered, but the shadow fading is not taken into account.

Fig. 7 illustrates the resulting distribution of the signal-to-interference ratio in one investigated scenario. See [15] for details and further references. In the scenario, the SIR due to path loss becomes at least 5 dB at cell edges and the average of the SIR in decibels over the cell area becomes around 16 dB.

The results in Fig. 8 use a normalized maximum carrier-to interference ratio scheduler that selects the terminal with the best SIR relative to its own average SIR (dB), out of K active users. For users with equal fading statistics and nonempty queues, this scheduling will maximize the spectral efficiency under the constraint of position-independent access to bins. The users are distributed randomly and uniformly over the sector area.

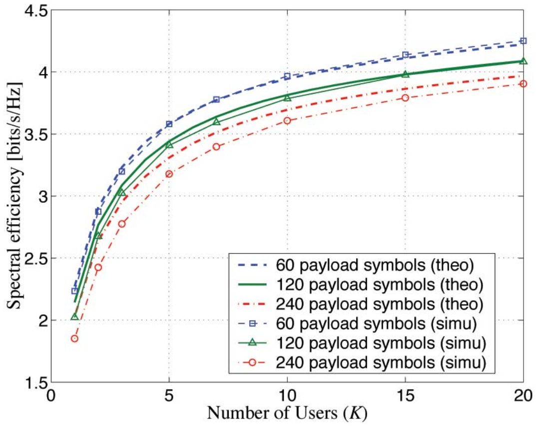

Fig. 6. ***Simulated spectral efficiency for different bin sizes, when using max throughput scheduling of*** K ***users, all with average SINR 16 dB. A Rayleigh-fading two-tap channel with second-tap delay 800 ns and damping 10 dB and terminal velocity 50 km/h is used. Pilot and control overhead is not included. Multilink simulations use an uncoded adaptive modulation scheme based on perfect SINR predictions, using 1, 2, . . ., 7, 8 bits per symbol, with rate limits optimized for maximal throughput. Changing the bin size here changes the packet size and the optimized modulation thresholds. These effects produce the theoretical (theo) results for channels that are constant within bins. Simulation results (simu) also show the effects of channel variations within bins. Please see [30] for further details.***

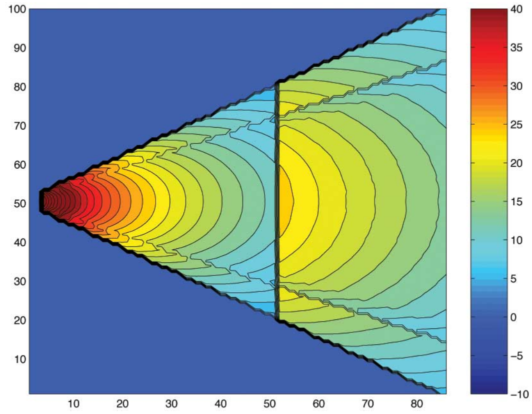

Fig. 7. ***Distribution of the average SIR in decibels due to path loss within a 60° sector, for one particular setting of the boundary between the high-SIR zone 1 close to the base station and zone 2 in the outer part of the triangular sector. The axes are scaled by the cell radius $*$ 100. Fully loaded interfering cells and path loss propagation exponent 4 are assumed. The inner zone 1 is affected by interference from 36 sites (three tiers), while 12 sites interfere in the outer zone 2. Shadow fading is not included. (With shadow fading, the zone boundary would not be a line, it would be determined by the SIR.)***

Uncoded adaptive modulation with 1, 2, . . ., 7, 8 bits per symbol is used, based on perfect channel prediction.

The sector payload capacity obtained in Fig. 8 for average sector SIR 16 dB is very similar to the theoretical results obtained in [30], where all users have equal SIR 16 dB and max throughput scheduling is used, scaled down by the reuse factor (here 1.73). The form of the curves and the multiuser scheduling gain as function of K remains unaltered.

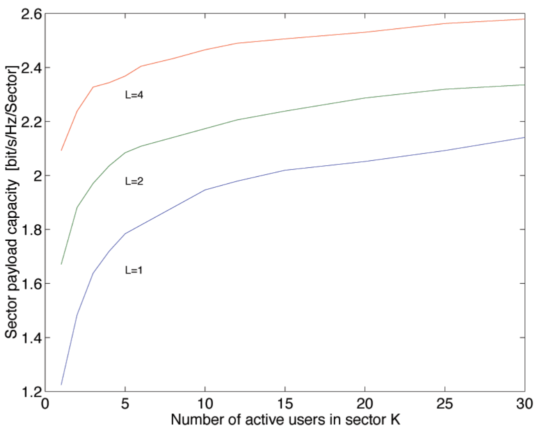

Fig. 8. ***Estimated sector payload capacity for a hexagonal site pattern with 60° sectors for Rayleigh-fading channels, as a function of the number K of uniformly distributed users, each using L receiver antennas that use maximum ratio combining. Pilot and control overhead as in Fig. 4 and reuse factors are included. Full system load and path loss exponent 4 is assumed. The zone boundary is 0.7 radii and the resulting frequency reuse factor is 1.73. Under the simulation assumptions, this maximizes the spectral efficiency at full load.***

Fig. 8 also illustrates the effect of using L-antenna receivers that use maximum ratio combining. The same result would be obtained for MMSE transmit beamforming that uses L antennas and one receiver antenna. The performance improves with L, while the multiuser scheduling gain is reduced, since the combination of antenna signals reduces the channel fading. This effect is called *channel hardening* [120]. The influence of different multiantenna transmission schemes on the multiuser diversity is discussed in, e.g., [121].

4) *Impact of Frequency Offsets in OFDMA Uplink:* To avoid intercarrier interference (ICI) in an OFDMA uplink, accurate synchronization of the carrier frequency in each user terminal is needed. The frequency inaccuracy of received signals is related to the frequency stability of the local oscillator in the terminal and the Doppler shift due to user terminal mobility. The remaining oscillator drift after synchronization can be modeled as a slow stationary time-varying process.

In [122], a model is proposed for analyzing the frequency synchronization errors after the DFT demodulation process at the receiver. A synchronization mechanism is assumed in the uplink so that the frequency synchronization errors are unbiased. The remaining frequency offset for a subcarrier is assumed to be Gaussian distributed. We use the model to demonstrate the loss in spectral efficiency due to ICI that results from carrier frequency offsets.

Fig. 9 shows the simulation results under assumption of perfect channel prediction. All terminals have average SNR 16 dB and velocity 50 km/h. Channels are modeled with the ITU-IV Channel A, assumed to be independent

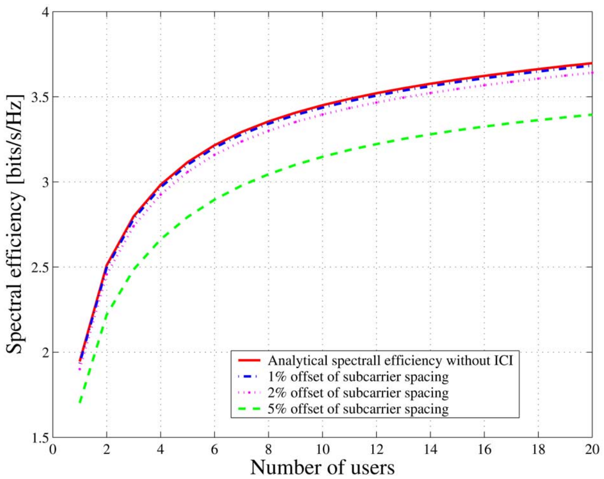

Fig. 9. ***Spectral efficiency as function of number of users, all with average SNR 16 dB and $L = 1$ receiver antenna, using max. throughput scheduling. Spectral efficiency obtained by an adaptive uplink multiuser OFDMA system with carrier frequency offsets of 0, 1%, 2% and 5% of the subcarrier spacing.***

Table 2 Example Parameter Sets for WINNER FDD and TDD Modes [31]

Parameter	FDD	TDD (Asymmetry 1:1)
Center frequency [GHz]	5.0 +/- 0.384	5.0
Number of subcarriers	1024	2048
FFT BW [MHz]	20.0	100.0
Signal BW [MHz]	2 x 16.25, paired	81.25
Number of used subcarriers	832	1664
Subcarrier spacing [Hz]	19531	48828
OFDM symbol duration [μs]	51.20	20.48
Cyclic prefix [μs]	5.00	0.80
Physical bin size [kHz x μs] (TDD incl. guard interval)	156.24 x 337.2	781.25 x (319.2+18)
Bin size in channel symbols (subcarriers x OFDM symb.)	8 x 6 = 48	16 x 15 = 240

and block fading over the bin duration. The same link adaptation as in Section V-A2 is used, see [122], for further details. The results show that a frequency inaccuracy or Doppler broadening of 1%–2% of the subcarrier spacing results in a spectral efficiency in the uplink close to the corresponding downlink (having no subcarrier offsets). A 2% (200 Hz) offset corresponds to 0.1 ppm of the carrier frequency in Table 2. This is a much tighter requirement than in present WLAN standards. Ongoing research within the WINNER project indicates that uplink synchronization with this accuracy is attainable.

5) Interaction With Higher Layers: We have stressed the need for low delays over the air interface. If the delays are low so that link retransmissions are fast, this allows a high maximal number of retransmissions (high persistence) to be used, to avoid packet losses. Packet losses on the link will trigger TCP retransmissions and may also invoke the TCP congestion avoidance mechanism, which slows down the transmission.

The results in Fig. 10, from [123], illustrate the TCP throughput over an emulated single-user link with adaptive modulation, as a function of the persistence of the retransmission scheme. The simulations use a simple channel scheduling algorithm that selects a single bin for transmission in each timeslot. The air-interface retransmission delay is low, 3 bin duration (slots), or 2.0 ms. Uncoded M-QAM is used and erroneous bin payloads are retransmitted, here without the use of soft combining. For low persistence, the throughput drops markedly, due to a combination of packet losses and invocation of the TCP congestion avoidance mechanism. The use of high persistence has no negative influence on the throughput. For the evaluated data rates, fixed network round-trip delays in the range 2–200 ms have a negligible influence on these results.

These results also illustrate the potential benefits of using channel scheduling as compared with using a static channel allocation scheme, and the reduction of the benefit due to channel prediction errors.[14] The potential and limitation of channel prediction is illustrated further in the section below.

B. The WINNER Design and Investigations

The results in Section V-A were obtained for 5 MHz channels at 2 GHz. The EU FP6 Integrated Projects WINNER and WINNER II explore broadband systems with bandwidths up to 100 MHz at frequencies up to 5 GHz. Here, we continue the exposition with results obtained within this framework. The assumed adaptive transmission system is similar to that of Section V-A, but it will be described here in more detail.

The design and evaluation is performed here at the highest considered WINNER carrier frequency of 5 GHz. This results in the most challenging test cases: At the shortest carrier wavelength, the fading is fastest for a given terminal velocity. The constraints on the feedback loop delays become tightest and the attainable prediction horizons become shortest. If frequency-adaptive transmission can be made to work here for moving terminals, it would work even better at lower carrier frequencies.

1) Medium Access Control (MAC): The WINNER MAC architecture presented in [17] and [26] is illustrated by Fig. 11 for downlinks. Radio link control (RLC) protocol data units (PDUs) are optionally segmented and each segment is encoded with an outer (turbo or LDPC) code.

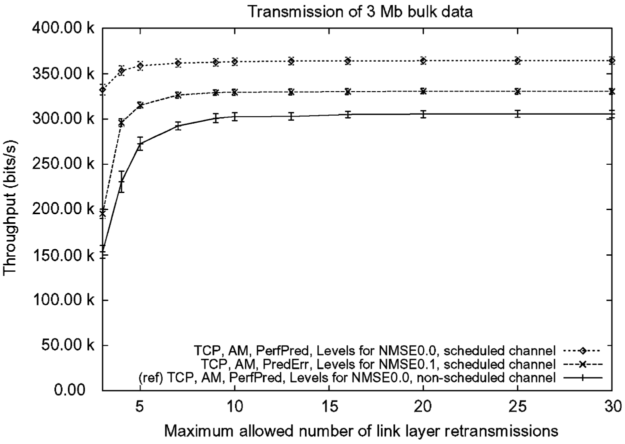

Fig. 10. ***TCP throughput versus allowed number of link layer retransmissions. One out of 25 bins of 200 kHz width is allocated to the flow in each frame. The upper curve shows the result for allocating the best out of 25 bins in each frame based on perfect prediction, while the middle curve shows the impact of rather large prediction errors (normalized prediction mean square error 0.1). At the bottom is the result using a fixed set of bins. All results use adaptive M-QAM, optimized to maximize throughput at infinite persistence also in the presence of prediction errors [45]. Velocity 75 km/h, 3GPP Typical Urban channel model with average SINR 16 dB, Rayleigh-fading, and 4 dB log-normal shadow fading are assumed. Please see [123] for additional assumptions.***

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[14] The multiuser scheduling gains are here limited by the use of a scheduling policy that provides guaranteed access in each slot (one out of 25 bins), in a rather narrow 5 MHz channel with limited frequency selectivity.

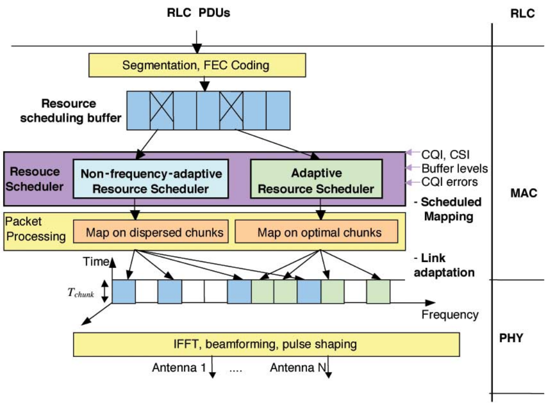

Fig. 11. ***WINNER scheduling architecture for downlinks.***

These code blocks may be queued per flow in a resource scheduling buffer. They are bit-interleaved and punctured at transmission to produce incremental redundancy for the later use by a hybrid ARQ scheme. They are then mapped onto bins (which in the WINNER projects are called *chunks*).

Frequency-adaptive transmission is used when feasible, up to a limiting velocity or down to a lower limiting average user SINR, see Table 3. It may use an optional inner (convolutional) code as part of the bin-specific link adaptation. Nonfrequency-adaptive transmission (mapping onto dispersed time-frequency-spatial resources, as described in Section III-C2) is used otherwise.[15]

A resource scheduler controls the mapping of flows onto appropriate resource units. Various scheduling algorithms can be used and compared in this context. This framework constitutes a testbed that accommodates the various combinations of encoding and link adaptations discussed in Section III-C1. Two alternatives will be compared in Section V-B6.

In general, each flow may use a multiantenna transmit scheme adjusted to its needs [18], [19]. A frequency-adaptive transmission design appropriate for base stations with single antennas or a fixed grid of beams is now outlined. We consider FDD downlinks and uplinks (mainly evaluated in wide-area scenarios), and TDD downlinks and uplinks (mainly for metropolitan and short-range scenarios). Table 2 shows the assumed bin sizes along with important system parameters.[16]

2) Frequency-Adaptive Control Loop for Half- and Full-Duplex FDD: An example design of bins is shown in Fig. 12 for FDD downlinks (left) and uplinks (right). A frame corresponds to two bin durations. Compared with the WIP design of Section V-A, the WINNER evaluation scenario works at a 2.5 times higher carrier frequency, with correspondingly shorter wavelength. This makes channel prediction more difficult at a given vehicle velocity. To shorten the required prediction horizon in time, the bin (slot) duration has been shortened.

We consider a terminal that is to receive data in slot number $i+2$ and to transmit in slot $i+3$. Assuming as in Section II-E that prediction and scheduling each require at most half a bin duration, transmission control loops that provide the lowest attainable delay can be described as follows.

FDD Downlink:

1) Beam-specific (dedicated) pilots (P) are transmitted on the downlink. Based on pilots received until the middle of slot i, all terminals with active downlinks predict the channel quality of all relevant bins in slot $i+2$. The prediction horizon to the end of slot $i+2$ is 2.5 bin durations which by Table 2 equals 0.843 ms.
2) Prediction reports are then source-coded and transmitted on uplink control symbols in slot $i+1$.
3) During the remainder of slot $i+1$, the scheduler calculates the allocation where in each beam, bins of slot $i+2$ are assigned exclusively to flows.
4) The user allocation and modulation/coding scheme (MCS) is then reported by downlink control symbols (D) embedded in the downlink bins in slot $i+2$. The payload is also transmitted in slot $i+2$ and is buffered at the receiver until the control messages have been decoded.

Control symbols need not be placed within the bins, as shown in Figs. 4 and 12, but if they are placed in this way, they can after decoding be used as extra regressor variables for (decision-directed) channel prediction [38].

FDD Uplink: In the uplink of slot $i-1$, a request is sent by the terminal for granting uplink transmission during slot $i+3$. Channel predictions for the uplinks must in FDD be based on uplink measurements. If uplink channels at slot $i+3$ are to be predicted for a set of terminals, then *all* these terminals must send uplink pilots in slot $i+1$. We assume here that the terminals use the positions indicated by (O) in Fig. 12 to transmit pilots. The prediction horizon is then 2.5 slots or 0.843 ms. As mentioned in Section III-B, the required pilot overhead is a potential complication. To alleviate it, each terminal may be competing for only a part of the bandwidth, here denoted a *competition band*.

During the later part of slot $i+1$ and the beginning of slot $i+2$, the scheduler assigns the uplink transmission. The allocation and link adaptation control information for slot $i+3$ is then transmitted over the downlink during slot $i+2$. In Fig. 12, in-chunk uplink control symbols (U) are indicated for this purpose. Alternatively, the transmission of these control bits could use separate downlink resources.

3) Frame Design and Adaptation Control Loop in TDD: An example of bin structure from [31] for the WINNER TDD

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[15] The use of the same two principles has been suggested in [11, Fig. 2].

[16] These parameters are subject to change during the WINNER II project.

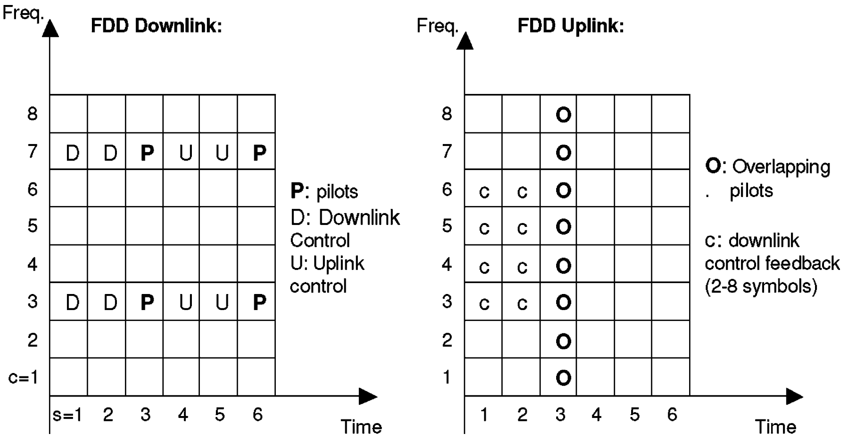

Fig. 12. ***Example design of WINNER bin structure for SISO FDD downlinks and uplinks. An FDD frame (0.6744 ms) equals two bin durations (slots) [31].***

mode is shown in Fig. 13.[17] In TDD operation, frames of neighboring base stations should preferably be synchronized and have the same uplink/downlink asymmetry. Otherwise, severe cross-slot interference problems will occur, with base station-to-base station interference and terminal-to-terminal interference. In addition, transmission-free duplex guard intervals are needed between each uplink and downlink slot, to prevent propagation delays from causing cross-slot interference.

The example design accommodates uplink/downlink asymmetry ratios between $1:2$ to $2:1$. The first ten OFDM symbols of a frame always belong to the uplink, and the last 11 OFDM symbols to the downlink. Depending on the uplink/downlink border, the uplink bin size may vary between $16 \times 10 = 160$ and $16 \times 19 = 304$ channel symbols.

The adaptation control loop for TDD works in a very similar way as for the FDD case described above. The main difference to the FDD case is that the channel reciprocity creates more freedom for the placement of the channel predictors. In the investigations of predictor performance presented in the subsection below, the predictions for both uplink and downlink are assumed to be performed by the terminals, based on downlink pilots and control symbols. The uplink interference would then have to be measured by the base station.[18]

Assume that regressor variables until the last pilot of the downlink slot i are used for predicting the to-be-scheduled downlink slot $i+2$ and uplink slot $i+3$. The required prediction horizon for the downlink is then 2.0 slots or 0.676 ms. Depending on the asymmetry ratio, the interval to the far end of the uplink slot $i+3$ varies between 0.91–1.08 ms. For asymmetry $1:1$, the required uplink prediction horizon is 1.00 ms. The prediction reports might be transmitted on the uplink control symbols (c), placed within the uplink bins as in Fig. 13. However, a better design is to use a separate physical control channel, that does not depend on the existence of active frequency-adaptive uplink flows within the cell.

4) Performance of Channel Prediction: The feedback loops presented above are designed to be as fast as possible, within realistic constraints imposed by computation times and signaling delays. Still, extrapolation of the present channel estimate would lead to large performance losses at > 10 km/h. To push the performance limits, channel prediction must be used.

The attainable prediction quality depends on the type of fading statistics, the pilot density, the prediction horizon scaled in carrier wavelengths, and the average SINR of the channel. In Fig. 14 from [31], [46], we show results for Rayleigh-fading [single-input–single-output (SISO)] FDD downlinks, obtained by frequency-domain Kalman prediction. A set of linear prediction filters is utilized, each responsible for its own subband. The state-space algorithm described in [38] predicts the complex time-varying channel coefficients and provides an MMSE-optimal prediction of the channel power gain.

The results are given for full duplex FDD terminals that use all time-slots for updating the predictor with measurements. The FDD downlink and pilot pattern of Section V-B2, Fig. 12, is investigated for white noise of known power and the WINNER Urban Macro channel [49]. The prediction error is represented by the NMSE, the mean square prediction error of the complex channel, normalized by the average channel power. Note the large dependence of the prediction performance on the SNR.

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[17] In this particular example, the uplink slot precedes the downlink slot of the frame. This choice is arbitrary and can be reversed.

[18] An alternative design is possible which places the channel predictors for one or both links at the base station. This solution would have to work with uplink pilots from all terminals, as in the FDD uplink case.

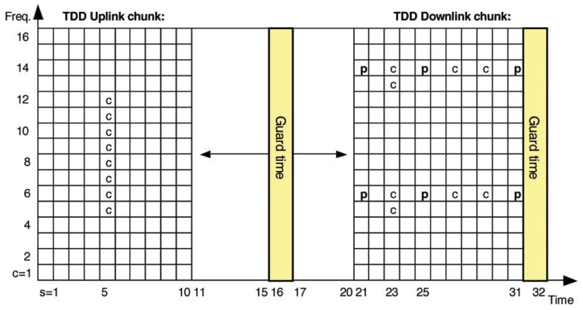

Fig. 13. ***Example design of WINNER TDD frame structure. One bin (chunk) width is illustrated with pilot and control symbol patterns and guard intervals between uplink and downlink slots. The squares represent channel symbols. The frame duration equals two bin durations + two guard intervals, see Table 2. The slot duration depends on the uplink/downlink asymmetry ratio. Each slot contains 104 bins within a 81.25 MHz signal bandwidth.***

Prediction performance of FDD uplinks, based on superposed (overlapping) uplink pilots, will result in a reduced accuracy with an increasing number of terminals, see the results in [31], [39], and [49]. However, this decrease is rather modest. Channel predictions in FDD uplinks in which not too many users occupy each competition band seems feasible.

Prediction investigations for the TDD design of Section V-B3 show that, as compared with the FDD full duplex downlink, the accuracy is somewhat worse for a given prediction horizon, see [31]. This is due to the half-duplex transmission, which interrupts continuous transmission of pilots. The required prediction horizon is also longest for the TDD uplink.

Based on research on the effect of prediction uncertainty on adaptive modulation schemes that are designed to attain a target bit-error rate (BER) [44], we here provisionally introduce an upper limit of NMSE $= 0.15$ for the useful prediction accuracy. Above that limit, nonfrequency-adaptive transmission has to be used.

The required prediction horizons from Sections V-B2 and V-B3 are in Table 3 expressed as the prediction horizons in space that would be required at a given terminal velocity at 5 GHz carrier frequency. (At other carriers f, the corresponding velocities would then be scaled by 5 GHz/f.) Based on the performance investigation of channel predictors described above, Table 3 also indicates the SNR below which the prediction NMSE for the required prediction horizon is below the suggested maximum limit 0.15. Note that these results are for Rayleigh-fading statistics. For flatter Doppler spectra, the channel predictability is somewhat lower, while it is much better for more peaky spectra [39], [41].

The best results (lowest SNR limits) are obtained for FDD and TDD downlinks. The most difficult situations are obtained for high velocities in the assumed TDD uplinks (that require the longest prediction horizons) and in the FDD uplinks with many users in the competition band (requiring the base station to estimate many channel parameters).

Based on these investigations, frequency-adaptive transmission can be expected to work in a wide variety of scenarios and SINRs, also at vehicular velocities.

Table 3 Required Prediction Horizons and Estimates of the Minimum SNR on Rayleigh-Fading Channel That Enable Frequency-Adaptive Transmission. Results for 5 GHz Carrier

Link	30 km/h	50 km/h	70 km/h
TDD downlink	0.094λ < 0 dB	0.156λ 5 dB	0.219λ 10 dB
TDD uplink (Asymmetry 1:1)	0.150λ 5 dB	0.25λ 15 dB	0.35λ > 25 dB
FDD downlink (Cf. Fig. 14)	0.117λ < 0 dB	0.195λ 6 dB	0.273λ 12.5 dB
FDD uplink, Kalman prediction for 2 users	0.117λ 0 dB	0.195λ 7 dB	0.273λ 15 dB
FDD uplink, Kalman prediction for 8 users	0.117λ 3.5 dB	0.195λ 11 dB	0.273λ 20 dB

5) Multiuser Scheduling Gains With Uncertain Channel Quality Prediction: In this section, we focus on the FDD SISO downlink and highlight the attainable multiuser scheduling gains in the WINNER scenario under simplified assumptions on especially traffic models and user behavior. Please see [31], [46], and [63] for further details and discussions.

The multilink simulations assume the FDD parameters and bin structure of Table 2, Section V-B2, and the channel prediction performance shown by Fig. 14. Proportional fair scheduling is used under a full buffer assumption. All users have Rayleigh-fading channels with

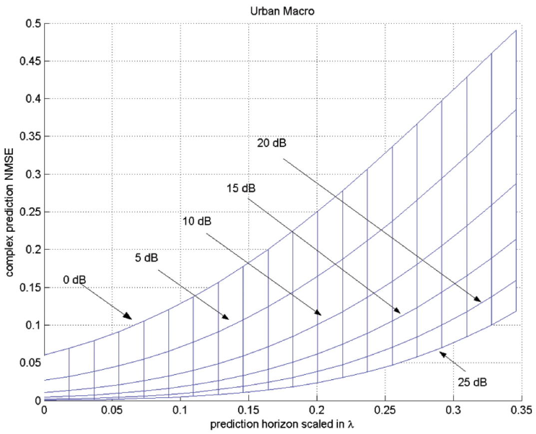

Fig. 14. ***Normalized mean square prediction error (NMSE) for Rayleigh-fading channels, as a function of the prediction horizon scaled in carrier wavelengths, for different SNR (0–25 dB) with white noise. Results for full duplex FDD downlinks over WINNER Urban Macro channels, with each Kalman prediction algorithm utilizing 8 pilot-bearing subcarriers.***

the same average SNR and have the same velocity. The terminals can be scheduled within the whole signal bandwidth.

Link adaptation is performed here by adaptive M-QAM combined with bin-specific (inner) convolutional coding. No outer coding is used. The channel gain varies within each bin. The modulation and code rate potentially used by each user in a bin is based here on the average predicted bin-SINR, $\mathrm{SINR}_{\mathrm{av}}$, and on the predicted SINR, SINR_w, at the worst location within the bin. Their weighted average in decibels is used as the *effective bin SINR* as $\mathrm{SINR} = b\mathrm{SINR}_{\mathrm{av}} + (1-b)\mathrm{SINR}_w$, with $b = 0.4$ used in Figs. 15 and 16.

Fig. 15 shows the combined multiuser scheduling and link adaptation gains when using TDMA/OFDMA. The assumed channel prediction error levels correspond to two different SNR (10 and 19 dB) combined with different terminal velocities. From the NMSE = 0.15 − limit used in Table 3, we could expect in the FDD downlink case that the adaptation scheme should work rather well for all investigated velocities up to 70 km/h at 19 dB (prediction 0.293λ ahead, giving NMSE 0.0937 by Fig. 14), but that difficulties may be encountered at 70 km/h when the SINR is only 10 dB (NMSE 0.1783). The results in Fig. 15 are indeed in accordance with the guidelines of Table 3 for Rayleigh-fading channels.

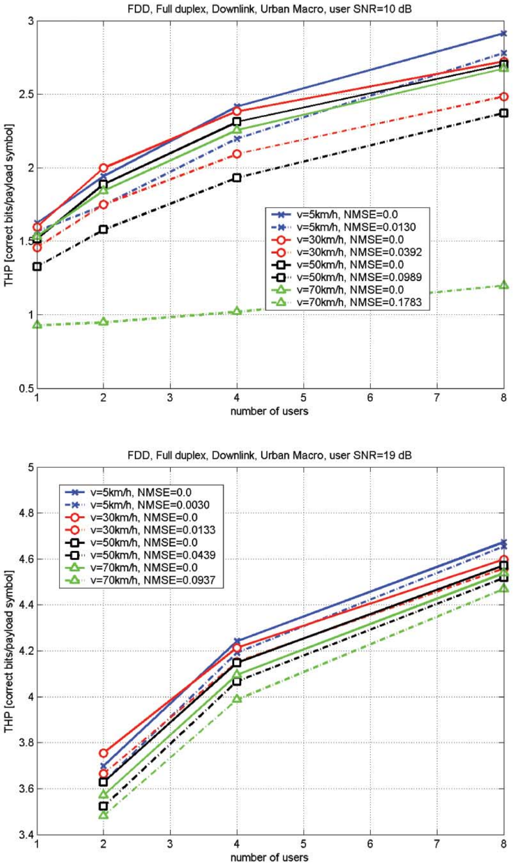

Fig. 15. ***Throughput as a function of the number of active users, all with the same average SNR of 10 dB (top) and 19 dB (bottom) in FDD downlinks with 16.25 MHz signal bandwidth, see Table 2. Solid curves take channel variability within bins into account but neglect the prediction uncertainty. Dashed curves include also prediction uncertainty, according to Fig. 14. The link adaptation is adjusted per bin and utilizes eight rates: BPSK rate 1/2, QPSK rate 1/2, QPSK rate 3/4, 16-QAM rate 1/2, 16-QAM rate 2/3, 16-QAM rate 5/6, 64-QAM rate 2/3, and 64-QAM rate 5/6. Rate limits maximize throughput under a maximal BER constraint of 10^{-3}, to be fulfilled also for uncertain predictions [31].***

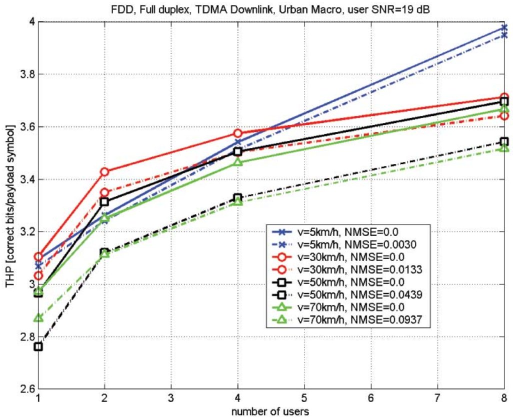

Fig. 16. ***Throughput results at 19 dB with a TDMA scheduling constraint in the 16.25 MHz signal bandwidth of the FDD downlinks of Table 2. One user is given all 104 bins within a slot. Individual bin-based link adaptation. Other conditions as in the lower part of Fig. 15.***

Section V-A1 indicated the usefulness of allocating frequency resources to users in frequency-selective channels. Therefore, we investigate here the loss of performance when using a TDMA scheduling constraint instead of TDMA/OFDMA. In Fig. 16, the scheduler selects the user with highest sum-of-rates capacity within all 104 bins in the FDD downlink, and gives all of these bins to that user. (With a full buffer assumption, the problem of this allocated resource unit being too large is ignored here.) Comparing the results at 19 dB average user SINR in Figs. 15 to 16, we see that the throughput is significantly reduced. Approximately half of the multiuser scheduling gain, as measured by the slope $T(k+1) - T(k)$ of the throughput T as a function of the number of users k, is lost when using a TDMA scheduling constraint compared with TDMA/OFDMA. The reason is that there is less variability in the sum of the usable rates for the whole timeslot as compared with the rates in individual bins.

6) Channel Coding and Bin Based Resource Scheduling: With the bin size of Fig. 12 and link adaptation rates used in Section V-B5, a FDD bin accommodates between 18 and 180 payload bits. Such a small resource unit is useful for efficient transmission of small packets by using convolutional encoding, but cannot obtain higher channel coding gains by using stronger codes like turbo codes or LDPC codes.

Furthermore, a retransmission scheme is needed. The varying bin capacity makes it difficult to implement individual scheduling and link adaptation also for retransmitted packets in incremental redundancy-based hybrid ARQ (HARQ) schemes with soft combining.

In this section we address the question on how to best combine the bin-based fine-grained resource allocation strategy with efficient coding and for network layer packets. An adequate combination preserves the multiuser scheduling and link adaptation gains regardless of various sizes of packets and different reliability requirements.

To this end, we investigate the use of FEC encoding *before* resource scheduling, as illustrated in Fig. 11. This *outer FEC code* block has a size that is independent of bins later assigned by the resource scheduler, while the link adaptation is performed by adaptive modulation and puncturing. This strategy decouples the scheduling, link adaptation and HARQ processes. It also enables the use of larger code blocks.

In [63], we propose and discuss this approach and compare to the results in Section V-B5, where convolutional coding was applied locally per bin. That design will be denoted the "Inner code" case. All of the link adaptation rates in Section V-B5 use the same convolutional code. We use this code here as an outer code, perform bit interleaving, and use bin-specific puncturing in the link adaptation. The difference of this "Outer code" case to Section V-B5 is the larger FEC block and the extra bit-interleaver over multiple bins. All other simulation assumptions are the same as in Section V-B5.

The dashed curves in Fig. 17 show the performance in the "Inner code" case and the solid curves show the performance in the "Outer code" case. As seen in Fig. 17, when using the same packet size and b parameter value for the effective bin SINR calculation defined in Section V-B, there is an increase in throughput with the Outer code. This is due to the lower tail bits overhead in the Outer code case.

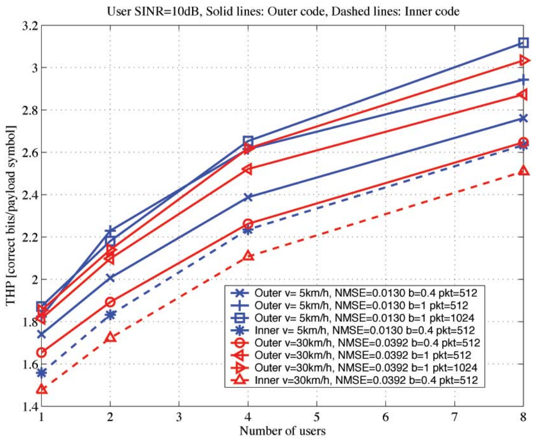

Fig. 17. ***Throughput as a function of the number of active users, all with the same average SNR of 10 dB in FDD downlink of Table 2, at user velocities 5 and 30 km/h. Prediction uncertainty with the given NMSE is taken into account and effective bin SINR, see Section V-B5, is calculated with $b = 0.4$ and $b = 1$, respectively, for two different code block sizes (512 and 1024 bits). Dashed lines: Inner code cases, solid lines: Outer code cases.***

Furthermore, the resulting BERs become smaller for the Outer code case. That can be used to set a more aggressive value for the b parameter, and still fulfill the target BER. As a result, a higher effective SINR is used in the link adaptation, and there is the potential for larger throughput. The simulation showed that the target BER is satisfied even with $b = 1$, i.e., when using the average SINR within bins for determining the link adaptation. This significantly improves the throughput.

This basic investigation using a convolutional code as the outer code showed a substantial increase in throughput. The results have motivated further work within the WINNER project on individual bin-wise link adaptation combined with coding over multiple bins, using strong codes. A very promising approach is to use a mutual-information effective SINR metric [124] for determining an average puncturing of a code block that spans multiple bins with different SINRs, that each use differing individual modulation. This technique was proposed and evaluated for LDPC codes by Stiglmayr in [64], and was applied with duo-binary turbo codes in [65], in both cases under the assumption of perfect channel prediction. Work on defining an accompanying HARQ scheme is ongoing.

VI. SUMMARY AND DISCUSSION

Our exposition has surveyed numerous aspects that affect the performance of adaptive OFDMA-based systems. Let us summarize some of them, with some additional comments.

- There are significant gains in utilizing the frequency variability of the channel, instead of just using the time-variability. This is enabled by the use of OFDMA. The resource units used (time-frequency bins) should be dimensioned with regard to the channel variability in time and frequency and the control signaling load.
- Adaptation feedback loops and retransmission systems can be designed to provide delays over the air interface on the order of a few milliseconds. This enables the use of frequency-adaptive transmission also at vehicular velocities, if channel quality prediction is employed. The multiuser scheduling gains in throughput promise to be much larger than the control signaling effort that is spent on enabling this type of transmission.
- Since adaptation of the small-scale frequency-selective fading cannot be used in all situations, a backup scheme based on diversity techniques, denoted here as nonfrequency-adaptive transmission, should be provided.

- Link adaptation and scheduling can for downlinks be decomposed into problems that can be solved with low computational complexity, enabling low transmission delays. Low-complexity combined scheduling and link adaptation algorithms for uplinks require further research. Channel prediction algorithms [39] and iterative decoding schemes ([26, Table B.2]) can also be designed with sufficiently low-computational delays.
- The low targeted delays enable the use of link retransmissions with high persistence. This was found to be advantageous for TCP traffic.

Finally, the use of intercell coordination on slower timescales enables load balancing, interference avoidance, and spectrum sharing between cells and also between operators. We have not had space to discuss these mechanisms in detail. They are, however, important for the total system economy and continued research on policies and algorithms is required here. Flexible spectrum management and interference management are likely to be crucial for the deployment of systems beyond 3G. ■

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REFERENCES

[1] R. H. Frenkiel, B. R. Badrinath, J. Borras, and R. D. Yates, "The infostation challenge: Balancing cost and ubiquity in delivering wireless data," *IEEE Pers. Commun.*, pp. 66–71, Apr. 2000.

[2] T. Otsu, I. Okajima, N. Umeda, and Y. Yamao, "Network architecture for mobile communications systems beyond IMT-2000," *IEEE Pers. Commun.*, pp. 31–37, Oct. 2001.

[3] J. Bingham, "Multicarrier modulation for data transmission: An idea whose time has come," *IEEE Commun. Mag.*, vol. 28, no. 5, pp. 5–14, May 1990.

[4] J. Chuang and N. Sollenberger, "Beyond 3G: Wideband wireless data access based on OFDM and dynamic packet assignment," *IEEE Commun. Mag.*, vol. 38, no. 7, pp. 78–87, Jul. 2000.

[5] A. Goldsmith, *Wireless Communications*. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[6] A. Svensson, "An overview of adaptive modulation schemes for known and predicted channels," *Proc. IEEE*, vol. 95, no. 12, Dec. 2007.

[7] R. Knopp and P. A. Humblet, "Multiple-accessing over frequency-selective fading channels" in *Proc. IEEE Conf. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Toronto, Canada, Sep. 27–29, 1995, p. 1326.

[8] A. Doufexi *et al.*, "A comparison of the HIPERLAN/2 and IEEE 802.11a wireless LAN standards," *IEEE Commun. Mag.*, vol. 40, no. 5, pp. 172–180, May 2002.

[9] *IEEE Standard for Local and Metropolitan Area Networks, Part 16: Air Interface for Fixed Broadband Wireless Access Systems*, IEEE P802.16a/D12, Feb. 2005.

[10] A. Ghosh, D. R. Wolter, J. G. Andrews, and R. Chen, "Broadband wireless access with WiMAX/802.16: Current performance benchmarks and future potential," *IEEE Commun. Mag.*, pp. 129–136, Feb. 2005.

[11] T. Kwon *et al.*, "Design and implementation of a simulator based on a cross-layer protocol between MAC and PHY layers in a WiBro Compatible IEEE 802.16e OFDMA System," *IEEE Commun. Mag.*, pp. 136–146, Dec. 2005.

[12] *Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall Description: Stage 2 (Release 8)*, 3GPP TS 36.300, Apr. 2007, V 8.0.0.

[13] H. Ekström, A. Furuskär, J. Karlsson, M. Meyer, S. Parkvall, J. Torsner, and M. Wahlquist, "Technical solutions for the 3G long-term evolution," *IEEE Commun. Mag.*, vol. 44, no. 3, pp. 38–45, Mar. 2006.

[14] [Online]. Available: www.signal.uu.se/Research/PCCwirelessIP.html

[15] M. Sternad, T. Ottosson, A. Ahlén, and A. Svensson, "Attaining both coverage and high spectral efficiency with adaptive OFDMA Downlinks," in *Proc. Veh. Technol. Conf. 2003-Fall*, Orlando, FL, Oct. 6–9, 2003, pp. 2486–2490.

[16] IST WINNER and WINNER II projects, partly funded by the European Commission. [Online]. Available: https://www.ist-winner.org

[17] M. Sternad, T. Svensson, and G. Klang, "The WINNER B3G system MAC concept," in *Proc. IEEE Veh. Technol. Conf. VTC06-Fall*, Montreal, Canada, Sep. 2006, pp. 1–5.

[18] M. Döttling, M. Sternad, G. Klang, J. von Häfen, and M. Olsson, "Integration of spatial processing in the WINNER B3G air interface design," in *Proc. IEEE Veh. Technol. Conf. VTC06-Spring*, Melbourne, Australia, May 2006, pp. 246–250.

[19] D3.4.1: The WINNER II air interface: Refined multi-antenna concepts, IST-4-027756 WINNER II, Nov. 2006. [Online]. Available: https://www.ist-winner.org

[20] D3.5: Proposal for the Best Suited Deployment Concepts for the Identified Scenarios and Related RAN Protocols, IST-2003-507581 WINNER, Dec. 2005. [Online]. Available: https://www.ist-winner.org

[21] B. Classon, P. Sartori, V. Nangia, X. Zhuang, and K. Baum, "Multi-dimensional adaptation and multi-user scheduling techniques for wireless OFDM systems," in *Proc. IEEE Int. Conf. Commun., ICC 2003*, Anchorage, AK, May 2003, pp. 2251–2255.

[22] K. Hooli, J. Lara, S. Pfletschinger, M. Sternad, and S. Thilakawardana, "RRM architecture for spectrum sharing in B3G systems," in *Proc. 15th Wireless World Research Forum (WWRF)*, Paris, France, Dec. 2005, WG1.

[23] L. Hanzo, M. Münster, B. J. Choi, and T. Keller, *OFDM and MC CDMA for Broadband Multi-User Communications, WLANs and Broadcasting*. Chichester, U.K.: Wiley, 2003.

[24] D. Lacroix, N. Gourard, and M. Alard, "OFDM with guard interval versus OFDM/Offset QAM for high data rate UMTS downlink transmission," in *Proc. IEEE Veh. Technol. Conf. VTC01-Fall*, Atlantic City, NJ, Oct. 2001, pp. 2682–2686.

[25] M. Muck, M. de Courville, and P. Duhamel, "A pseudorandom postfix OFDM modulator—Semi-blind channel estimation and equalization," *IEEE Trans. Signal Process.*, vol. 54, no. 3, pp. 1005–1017, Mar. 2006.

[26] D2.10: Final report on identified RI key technologies, system concept, and their assessment, IST-2003-507581 WINNER, Dec. 2005. [Online]. Available: https://www.ist-winner.org

[27] D. Falconer and S. Kaiser, Eds. "Broadband frequency domain-based air interface for future-generation wireless systems," in *Proc. Wireless World Research Forum Working Group 4 White Paper*, Sep. 2005. [Online]. Available: http://wg4.ww-rf.org

[28] P. Chan, E. Lo, R. Wang, E. Au, V. Lau, R. Cheng, W. Ho Mow, R. Murch, and K. B. Letaief, "The evolution path of 4G

networks: FDD or TDD?" *IEEE Commun. Mag.*, pp. 42–50, Dec. 2006.

[29] A. Gyasi-Agyei and S.-L. Kim, "Cross-layer multiservice opportunistic scheduling for wireless networks," *IEEE Commun. Mag.*, vol. 44, no. 6, pp. 50–57, Jun. 2006.

[30] W. Wang, T. Ottosson, M. Sternad, A. Ahlén, and A. Svensson, "Impact of multiuser diversity and channel variability on adaptive OFDM," in *Proc. IEEE Veh. Technol. Conf. VTC03-Fall*, Orlando, FL, Oct. 2003, vol. 1, pp. 547–551.

[31] D2.4: Assessment of adaptive transmission technologies, IST-2003-507581 WINNER, Feb. 2005. [Online]. Available: https://www.ist-winner.org

[32] T. Eriksson and T. Ottosson, "Feedback and adaptive modulation and scheduling in wireless systems," *Proc. IEEE*, vol. 95, no. 12, Dec. 2007.

[33] O. Edfors, M. Sandell, J.-J. van de Beek, S. K. Wilson, and P. O. Börjesson, "OFDM channel estimation by singular value decomposition," *IEEE Trans. Commun.*, vol. 46, no. 7, pp. 931–939, Jul. 1998.

[34] P. Hoeher, S. Kaiser, and P. Robertson, "Two-dimensional pilot-symbol-aided channel estimation by Wiener filtering," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process.*, 1997, pp. 1845–1848.

[35] G. Auer, "Analysis of pilot-symbol aided channel estimation for OFDM systems with multiple transmit antennas," in *Proc. IEEE Int. Conf. Commun. ICC' 04*, Paris, Jun. 2004, vol. 6, pp. 3221–3225.

[36] M. Sternad, T. Ekman, and A. Ahlén, "Power prediction on broadband channels," in *Proc. IEEE Veh. Technol. Conf. VTC01-Spring*, Rhodes, Greece, May 6–9, 2001, pp. 2328–2332.

[37] T. Ekman, M. Sternad, and A. Ahlén, "Unbiased power prediction on broadband channels," in *Proc. IEEE Veh. Technol. Conf. VTC02-Fall*, Vancouver, Canada, Sep. 24–28, 2002.

[38] M. Sternad and D. Aronsson, "Channel estimation and prediction for adaptive OFDM downlinks," in *Proc. IEEE Vehicular Techn. Conf. VTC03-Fall*, Orlando, FL, Oct. 2003, vol. 2, pp. 1283–1287.

[39] D. Aronsson and M. Sternad, "Kalman predictor design for frequency-adaptive scheduling of FDD OFDMA uplinks," in *Proc. IEEE Conf. Pers., Indoor Mobile Radio Commun. PIMRC*, Athens, Greece, Sep. 2007.

[40] A. Duel-Hallen, H. Hallen, and T.-S. Yang, "Long range prediction and reduced feedback for mobile radio adaptive OFDM systems," *IEEE Trans. Wireless Commun.*, vol. 5, no. 10, pp. 2723–2733, Oct. 2006.

[41] T. Ekman, "Prediction of mobile radio channels. modeling and design," Ph.D. dissertation, Signals and Systems, Uppsala Univ., Uppsala, Sweden, 2002. [Online]. Available: www.signal.uu.se/Publications/abstracts/a023.html

[42] A. Duel-Hallen, "Fading channel prediction and estimation for mobile radio adaptive transmission systems," *Proc. IEEE*, vol. 95, no. 12, Dec. 2007.

[43] H. Zhang, G. Amariucai, S. Wei, G. Ananthaswamy, and D. Goeckel, "Adaptive signaling under statistical measurement uncertainty," *Proc. IEEE*, vol. 95, no. 12, Dec. 2007.

[44] S. Falahati, A. Svensson, M. Sternad, and T. Ekman, "Adaptive modulation systems for predicted wireless channels," *IEEE Trans. Commun.*, vol. 52, no. 2, pp. 307–315, Feb. 2004.

[45] M. Sternad and S. Falahati, "Maximizing throughput with adaptive M-QAM based on imperfect channel predictions," in *Proc. IEEE Conf. on Personal, Indoor and Mobile Radio Comm. PIMRC*, vol. 3. Barcelona, Spain, Sep. 2004, pp. 2282–2293.

[46] M. Sternad, S. Falahati, T. Svensson, and D. Aronsson, "Adaptive TDMA/OFDMA for wide-area coverage and vehicular velocities," in *Proc. IST Mobile Veh. Commun. Summit*, Dresden, Jun. 19–23, 2005.

[47] M. Kobayashi, G. Caire, and D. Gesbert, "Transmit diversity versus opportunistic beamforming in data packet mobile downlink transmission," *IEEE Trans. Commun.*, vol. 55, no. 1, pp. 151–157, Jan. 2007.

[48] A. Tölli, M. Codreanu, and M. Juntti, "Compensation of non-reciprocal interference in adaptive MIMO-OFDM cellular systems," *IEEE Trans. Wireless Commun.*, vol. 6, no. 2, pp. 545–555, Feb. 2007.

[49] M. Sternad and D. Aronsson, "Channel estimation and prediction for adaptive OFDMA/TDMA uplinks based on overlapping pilots," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process.*, Philadelphia, Mar. 19–23, 2005, vol. 3, pp. iii/861– iii/864.

[50] M. Döttling, B. Raaf, and J. Michel, "Efficient channel quality feedback schemes for adaptive modulation and coding of packet data," in *Proc. IEEE Veh. Technol. Conf. VTC04-Fall*, Los Angeles, CA, Sep. 2004, pp. 1243–1247.

[51] M. Johansson, "Benefits of multiuser diversity with limited feedback," in *Proc. IEEE Signal Processing Advances for Wireless Commun. SPWAC 2003*, Rome, Italy, Jun. 2003, pp. 155–159.

[52] D. Gesbert and M.-S. Alouini, "How much feedback is multi-user diversity really worth?" in *Proc. Int. Conf. Commun. ICC04*, Paris, France, Jun. 2004, pp. 234–238.

[53] Y.-J. Choi, J. Kim, and S. Bahk, "QoS-aware selective feedback and optimal channel allocation in multiple shared channel environments," *IEEE Trans. Wireless Commun.*, vol. 5, no. 11, pp. 3278–3286, Nov. 2006.

[54] K. Huang, R. W. Heath, and J. G. Andrews, "Space division multiple access with a sum feedback rate constraint," *IEEE Trans. Signal Process.*, vol. 55, no. 7, pp. 3879–3891, Jul. 2007.

[55] M. Johansson, "Resource allocation under uncertainty: Applications in mobile communications," Ph.D. dissertation, Uppsala Univ., Uppsala, Sweden. [Online]. Available: www.signal.uu.se/Publications/abstracts/a041.html

[56] T. Tang, R. Heath, S. Cho, and S. Yun, "Opportunistic feedback for multiuser MIMO systems with linear receivers," *IEEE Trans. Commun.*, vol. 55, no. 5, pp. 1020–1032, May 2007.

[57] D. J. Love, R. W. Heath, W. Santipach, and M. Honig, "What is the value of limited feedback for MIMO channels?" *IEEE Commun. Mag.*, pp. 54–59, Oct. 2004.

[58] T. T. Kim, M. Bengtsson, E. G. Larsson, and M. Skoglund, "Combining short-term and long-term channel state information over correlated MIMO channels," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process.*, Toulouse, France, May 2006, p. IV.

[59] J. Love, "Duplex distortion models for limited feedback MIMO communication," *IEEE Trans. Signal Process.*, vol. 54, no. 2, pp. 766–773, Feb. 2006.

[60] V. Lau, Y. Liu, and T.-A. Chen, "On the design of MIMO block-fading channels with feedback-link capacity constraints," *IEEE Trans. Commun.*, vol. 52, no. 1, pp. 62–70, Jan. 2004.

[61] P. Ding, D. J. Love, and M. D. Zoltowski, "Multiple antenna broadcast channels with shape feedback and limited feedback," *IEEE Trans. Signal Process.*, vol. 55, no. 7, pp. 3417–3428, Jul. 2007.

[62] S. Pfletchinger, "The influence of link adaptation in multi-user OFDM," in *Proc. 6th Int. Workshop Multi-Carrier Spread Spectrum*, Oberpfaffenhofen, Germany, May 2007.

[63] T. Svensson, S. Falahati, and M. Sternad, "Coding and resource scheduling in packet oriented adaptive TDMA/OFDMA systems," in *Proc. IEEE Veh. Technol. Conf. VTC06-Spring*, Melbourne, Australia, May 2006, pp. 1600–1604.

[64] S. Stiglmayr, M. Bossert, and E. Costa, "Adaptive coding and modulation in OFDM systems using BICM and rate-compatible punctured codes," *Eur. Wireless*, Apr. 2007, Paris.

[65] S. Pfletschinger, A. Piatyszek, and S. Stiglmayr, "Frequency-selective link adaptation using duo-binary turbo codes in OFDM systems," in *Proc. IST Mobile Wireless Commun. Summit*, Budapest, Hungary, Jul. 2007.

[66] B. Classon, K. Blankenship, and V. Desai, "Channel coding for 4G systems with adaptive modulation and coding," *IEEE Wireless Commun.*, vol. 1, no. 2, pp. 8–13, Apr. 2002.

[67] R. Laroia, S. Uppala, and J. Li, "Designing a mobile broadband wireless access network," *IEEE Signal Process. Mag.*, vol. 21, no. 5, pp. 20–28, Sep. 2004.

[68] A. Persson, T. Ottosson, and E. G. Ström, "A unified analysis for coded DS-CDMA with equal-gain chip combining in the downlink of OFDM systems," *IEEE Trans. Commun*, vol. 53, pp. 289–298, Feb. 2005.

[69] S. Plass and T. Svensson, "Block-equidistant resource mapping in OFDM, MC-CDMA and SS-MC-MA," in *Proc. 12th Int. OFDM Workshop*, Hamburg, Germany, Aug. 2007.

[70] D4.6.1: The WINNER II air interface: Refined multiple access concepts, IST-4-027756 WINNER II, Nov. 2006. [Online]. Available: https://www.ist-winner.org

[71] T. Svensson, T. Frank, D. Falconer, M. Sternad, E. Costa, and A. Klein, "B-IFDMA—A power efficient multiple access scheme for non-frequency-adaptive transmission" in *Proc. IST Mobile Wireless Commun. Summit*, Budapest, Hungary, Jul. 2007.

[72] W. Wang, T. Ottosson, T. Svensson, A. Svensson, and M. Sternad, "Evaluations of a 4G uplink system based on adaptive single-carrier TDMA," in *Proc. IEEE 62nd Veh. Technol. Conf. VTC05-Fall*, Dallas, TX, Sep. 25–28, 2005.

[73] W. Yu and J. P. Cioffi, "Constant power water-filling: Performance bound and low-complexity implementation," *IEEE Trans. Commun.*, vol. 54, no. 1, pp. 23–28, Jan. 2006.

[74] D. Tse, "Optimal power allocation over parallel Gaussian broadcast channels," in *Proc. IEEE ISIT*, Jul. 1997.

[75] G. Caire and S. Shamai, "On the achievable throughput of a multi-antenna Gaussian broadcast channel," *IEEE Trans. Inform. Theory*, vol. 49, no. 7, pp. 1691–1706, Jul. 2003.

[76] Q. H. Spencer, C. B. Peel, L. Swindlehurst, and M. Haardt, "An introduction to the multi-user MIMO downlink," *IEEE Commun. Mag.*, pp. 60–67, Oct. 2004.

[77] G. Del Galdo and M. Haardt, "Comparison of zero-forcing methods for downlink spatial multiplexing in realistic multi-user MIMO channels," in *Proc. IEEE Veh. Technol. Conf. VTC04-Spring*, Milan, Italy, May 2004, vol. 1, pp. 299–303.

[78] Y. J. Zhang and K. B. Letaief, "An efficient resource-allocation scheme for spatial multiuser access in MIMO/OFDM systems," *IEEE Trans. Commun.*, vol. 53, no. 1, pp. 107–116, Jan. 2005.

[79] M. Fuchs, G. Del Galdo, and M. Haardt, "A novel tree-based scheduling algorithm for the downlink of multi-user MIMO systems with ZF beamforming," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process. (ICASSP)*, Philadelphia, PA, Mar. 2005, vol. 3, pp. 1121–1124.

[80] S. Savazzi, M. Nicoli, and M. Sternad, "Spatial multiplexing for outdoor MIMO-OFDM systems with limited feedback constraints," in *Proc. IEEE Int. Conf. Commun. ICC' 06*, Istanbul, Turkey, vol. 1, Jun. 2006, pp. 73–78.

[81] R. S. Cheng and S. Verdú, "Gaussian multiaccess channels with ISI: Capacity region and multiuser water-filling," *IEEE Trans. Inform. Theory*, vol. 39, no. 3, pp. 773–785, May 1993.

[82] W. Yu, W. Rhee, S. Boyd, and J. M. Cioffi, "Iterative water-filling for Gaussian vector multiple access channels," *IEEE Trans. Inform. Theory*, vol. 50, no. 1, pp. 145–152, Jan. 2004.

[83] S. Pfletchinger, "From cell capacity to subcarrier allocation in multi-user OFDM," in *Proc. IST Mobile and Wireless Communication Summit*, Dresden, Germany, Jun. 2005.

[84] I. Kim, I.-S. Park, and Y. H. Lee, "Use of linear programming for dynamic subcarrier and bit allocation in multiuser OFDM," *IEEE Trans. Veh. Technol.*, vol. 55, no. 4, pp. 1195–1207, Jul. 2006.

[85] D. Gesbert, G. E. Øien, A. Gjendemsjø, and S. G. Kiani, "Adaptive transmission and resource allocation for multicell capacity maximization," *Proc. IEEE*, vol. 95, no. 12, Dec. 2007.

[86] Y. Cao and V. O. K. Li, "Scheduling algorithms in broad-band wireless networks," *Proc. IEEE*, vol. 89, no. 1, pp. 76–87, Jan. 2001.

[87] M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, and P. Whiting, "Providing quality of service over a shared wireless link," *IEEE Commun. Mag.*, vol. 39, no. 2, pp. 150–154, Feb. 2001.

[88] A. K. Parekh and R. G. Gallager, "A generalized processor sharing approach to flow control in integrated service networks: The single-node case," *IEEE/ACM Trans. Netw.*, vol. 1, pp. 344–357, Jun. 1993.

[89] K. Norlund, T. Ottosson, and A. Brunstrom, "Fairness measures for best effort traffic in wireless networks," in *Proc. IEEE Conf. Pers. Indoor, Mobile Radio Commun. (PIMRC)*, Barcelona, Spain, Sep. 2004, pp. 2953–2957.

[90] N. C. Ericsson, "Revenue maximization in resource allocation: Applications in wireless communication networks," Ph.D. dissertation, Uppsala Univ., Uppsala, Sweden, Sep. 2004, 91-506-1773-7.

[91] Z. Shen, J. G. Andrews, and B. L. Evans, "Adaptive resource allocation in multiuser OFDM systems with proportional rate constraints," *IEEE Trans. Wireless Commun.*, vol. 4, no. 6, pp. 2726–2737, Nov. 2005.

[92] P. Bender *et al.*, "CDMA/HDR: A bandwidth-efficient high-speed wireless data service for nomadic users," *IEEE Commun. Mag.*, vol. 38, pp. 70–77, Jul. 2000.

[93] J. M. Holtzman, "Asymptotic analysis of proportional fair algorithm," in *IEEE Conf. Pers., Indoor, Mobile Radio Commun. PIMRC*, San Diego, CA, Sep. 2001, vol. 2, pp. F-33–F-37.

[94] L. Yang and M.-S. Alouini, "Performance analysis of multiuser selection diversity," *IEEE Trans. Veh. Technol.*, vol. 55, no. 6, pp. 1848–1861, Nov. 2006.

[95] T. Bonald, "A score-based opportunistic scheduler for fading mobile radio channels," in *Proc. Eur. Wireless Conf.*, Barcelona, Spain, Feb. 2004.

[96] D. Park, H. Seo, H. Kwon, and B. G. Lee, "Wireless packet scheduling based on the cumulative distribution function of user transmission rates," *IEEE Trans. Commun.*, vol. 53, no. 11, pp. 1919–1929, Nov. 2005.

[97] X. Liu, E. K. P. Chong, and N. B. Shroff, "Opportunistic transmission scheduling with resource-sharing constraints in wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 10, pp. 2053–2064, Oct. 2001.

[98] S. Shakkottai and A. Stolyar, "Scheduling for multiple flows sharing a time-varying channel: The exponential rule," in *American Mathematical Society Translations*, ser. 2, Y. M. Suhiv, Ed., 2002.

[99] H. Boche and M. Wiczanowski, "The interplay of link layer and physical layer under MIMO enhancement: Benefit and challenges," *IEEE Wireless Commun.*, vol. 13, pp. 48–61, Aug. 2006.

[100] M. Johansson, "Diversity-enhanced equal access: Considerable throughput gains with 1-bit feedback," in *Proc. IEEE SPAWC, Workshop Signal Processing Wireless Commun.*, Lisbon, Portugal, Jul. 2004, pp. 6–10.

[101] V. Hassel, M. Røed Hansen, and G. Øien, "Spectral efficiency and fairness for opportunistic round robin scheduling," in *Proc. IEEE Int. Conf. Commun., ICC' 06*, Istanbul, Jun. 2006, pp. 784–789.

[102] P. Liu, R. Berry, and M. L. Honig, "Delay-sensitive packet scheduling in wireless networks," in *Proc. IEEE Wireless Commun. Netw. Conf. WCNC 2003*, Mar. 2003, pp. 1627–1632.

[103] S. C. Borst and P. Whiting, "Dynamic channel-sensitive scheduling algorithms for wireless data throughput optimization," *IEEE Trans. Veh. Technol.*, vol. 52, no. 3, pp. 569–586, May 2003.

[104] V. Hassel, "Design issues and performance analysis for opportunistic scheduling algorithms in wireless networks," Ph.D. dissertation, Norwegian Univ. Science and Technology NTNU, Trondheim, Norway, 2007:27.

[105] M. Johansson and M. Sternad, "Resource allocation under uncertainty using the maximum entropy principle," *IEEE Trans. Inform. Theory*, vol. 51, no. 12, pp. 4103–4117, Dec. 2005.

[106] J. Huang, R. A. Berry, and M. L. Honig, "Wireless scheduling with hybrid ARQ," *IEEE Trans. Wireless Commun.*, vol. 4, no. 6, pp. 2801–2810, Nov. 2005.

[107] G. Song and Y. Li, "Utility-based resource allocation and scheduling in OFDM-based wireless broadband networks," *IEEE Commun. Mag.*, vol. 43, no. 12, pp. 127–134, Dec. 2005.

[108] J. Rhee, J. M. Holtzman, and D. Kim, "Scheduling of real/non-real time services: Adaptive EXP/PF algorithm," in *Proc. IEEE Veh. Technol. Conf. VTC03-Spring*, Apr. 2003, vol. 1, pp. 462–466.

[109] W.-H. Park, S. Cho, and S. Bahk, "Scheduler design for multiple traffic classes in OFDMA networks," in *Proc. IEEE Int. Conf. Commun., ICC' 06*, Istanbul, Turkey, Jun. 2006, pp. 790–795.

[110] K. W. Choi, D. G. Jeon, and W. S. Jeon, "Packet scheduler for mobile communications system with time-varying capacity region," *IEEE Trans. Wireless Commun.*, vol. 6, no. 3, pp. 1034–1045, Mar. 2007.

[111] M. Lindström, L. Badia, J. Zander, and M. Zorzi, "Speculative resource allocation for packet-switched wireless networks," in *Proc. IEEE Veh. Technol. Conf. VTC05-Spring*, Stockholm, Sweden, Jun. 2005, pp. 1451–1455.

[112] C. W. Leong, W. Zhuang, Y. Cheng, and L. Wang, "Optimal resource allocation and adaptive call admission control for voice/data integrated cellular networks," *IEEE Trans. Veh. Technol.*, vol. 55, no. 2, pp. 654–669, Mar. 2006.

[113] W. Li and X. Chao, "Call admission control for an adaptive heterogeneous multimedia mobile network," *IEEE Trans. Wireless Commun.*, vol. 6, no. 2, pp. 515–525, Feb. 2007.

[114] M. K. Karakayali, G. Foschini, and R. A. Valenzuela, "Network coordination for spectrally efficient communications in cellular systems," *IEEE Wireless Commun.*, vol. 13, pp. 56–61, Aug. 2006.

[115] I. Katzela and M. Naghshineh, "Channel assignment schemes for cellular mobile telecommunication systems: A comprehensive summary," *IEEE Pers. Commun.*, vol. 3, no. 3, Jun. 1996.

[116] N. Feng, S.-C. Mau, and N. B. Mandayam, "Pricing and power control for joint network-centric and user-centric radio resource management," *IEEE Trans. Commun.*, vol. 52, no. 9, pp. 1547–1557, Sep. 2004.

[117] G. Li and H. Liu, "Downlink radio resource allocation for multi-cell OFDMA system," *IEEE Trans. Wireless Commun.*, vol. 5, no. 12, pp. 3451–3459, Dec. 2006.

[118] S. W. Halpern, "Reuse partitioning in cellular systems," in *Proc. IEEE Veh. Technol. Conf.*, 1983, pp. 322–327.

[119] A. Persson, T. Ottosson, and G. Auer, "Inter-sector scheduling in multi-user OFDM," in *Proc. IEEE Int. Conf. Commun, ICC'06*, Istanbul, Turkey, Jun. 2006, pp. 4415–4419.

[120] B. M. Hochwald, T. L. Marzetta, and V. Tarokh, "Multi-antenna channel hardening and its implication for rate feedback and scheduling," *IEEE Trans. Inform. Theory*, vol. 50, no. 9, pp. 1893–1909, Sep. 2004.

[121] C.-J. Chen and L.-C. Wang, "A unified capacity analysis for wireless systems with joint antenna and multiuser diversity in Nakagami fading channels," *IEEE Trans. Commun.*, vol. 54, no. 3, pp. 419–478, Mar. 2006.

[122] W. Wang, T. Ottosson, and T. Svensson, "Performance of an adaptive multiuser

OFDM uplink with carrier frequency offsets," in *IEEE Veh. Technol. Conf. VTC06-Spring*, Melbourne, Australia, May 2006, pp. 216–220.

[123] S. Alfredsson, A. Brunstrom, and M. Sternad, "Transport protocol performance over 4G links: Emulator methodology and results," in *Proc. Int. Symp. Wireless Commun. Syst. ISWCS*, Valencia, Spain, Sep. 5–8, 2006.

[124] K. Brueninghaus, D. Astély, T. Sälzer, S. Visuri, A. Alexiou, S. Karger, and G.-A. Seraj, "Link performance models for system level simulations of broadband radio access systems," in *Proc. IEEE Pers., Indoor, Mobile Radio Commun, PIMRC*, vol. 4. Berlin, Germany, Sep. 2005, pp. 2306–2311.

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