A conceptual study of OFDM-based multiple access schemes: Part 1 - Air interface requirements

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A Conceptual Study of OFDM-based Multiple Access Schemes

Part 1: Air Interface Requirements

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Abstract: **The multimedia era has started. The migration of computer (packet oriented) and telephony (circuit switched) networks in combination with an explosive development of new services, creates a mass market for public broadband communication. There are no reasons foreseen why these kind of services should not go mobile. Future customers will not treat a mobile access differently than a fixed access to the network. The different types of services together with the demand of broadband mobile communication requires a new air interface. Limitations in the existing systems (flexibility and bit-rate) gives that they are not serious competitors.**

I. INTRODUCTION

Multimedia services are no longer a topic for the future. The evolution of high bit-rate modems (20-50 Mbps) that can operate in existing mediums (i.e copper wire, twisted pair) will make it possible to provide cheap broadband services to a wide range of subscribers in a very near future [1]. This will result in a whole set of new services that include voice, high quality audio, images and data. The future service profile will also consist of distributed applications that require both execution environment and distribution transparencies (such as applications based on Java [2]). It is assumed that these new services, initially offered in the fixed network, will create a market for mobile multimedia.

A likely scenario is that GSM will evolve General Packet Radio Services (GPRS) and High Speed Circuit Switched Data (HSCSD). According to this scenario an evolved GSM would provide about 64 - 100 kbps in all kinds of radio environments. Other systems such as DECT and RadioLAN:s will support much higher bit rates (up to DECT: 500 kbps, RadioLAN: 20 Mbps) but are mainly designed for “nice” environments and have problems with severe Doppler and delay spread. This implies that one of the most important issues for a third generation mobile communication system is to support high bit-rates in “tough” radio environments. This future system is often referred to as UMTS - Universal Mobile Telecommunication System.

II. UMTS REQUIREMENTS

In order to identify the requirements of a third generation air interface it is important to study the GSM system.

The GSM system is a success. During the last couple of years, the GSM system has been able to provide speech services in almost all of Europe. The system is designed and optimized for the speech service and handles it in a spectrum efficient way. Foreseen capacity problems are solved with the DECT system and new frequency bands (DCS 1800). From an operators point of view it is therefore essential that a third generation mobile communication system is not optimized for speech, because the GSM system already exists and the potential market will include other kinds of service profiles than just the “plain old mobile telephony”.

Efforts to predict the “killer application” for mobile multimedia today, run the risk to be rather fruitless because of that the multimedia era just recently started. Since the requirements for the new services are unknown, it is also of great importance that the new air interface technique is flexible enough to handle as high bit rates as possible with various quality requirements. The possibility to handle high bit rates also implies that it should be the base station density that limits the usage of such services, *not* the radio interface technique in itself. A proper design of such an air interface is essential in order to be able to introduce services that are unknown today.

An assumed video codec for mobile purposes that utilise more than 100 kbps would, according to the above given scenario, be impossible to implement in an evolved GSM system regardless of the base station density. Limits that make it impossible to offer future conceivable services, could become fatal for an UMTS operator. This indicate the need of a new air interface. The new air interface should at least be able to carry 384 kbps, but with a target of 2 Mbps.

The limited bit rates derive from the restricted spectrum available for UMTS.

As foreseen today, a total bandwidth of 230 MHz are allocated to the UMTS system in the 2 GHz band [3]. Within this band the terrestrial services are allocated about 60 + 60 MHz (1920-1980, 2110-2170 MHz). The other parts of the band will be used for mobile satellite services and some overlap with the DECT system. With the assumption of an equal market competition as in the GSM system, each operator will be allocated around 15 + 15 MHz of spectrum for UMTS services. This is the same bandwidth as the block structure in the PCS system. Assuming a three level hierarchical cell structure layer (macro, micro and pico cell layers), around 5 + 5 MHz of bandwidth can be used in each cell.

The migration between the fixed and mobile networks will create a demand for support of packet traffic on the radio interface. As UMTS will be an intergrated part of the "telecommunication environment" any type of bearer service (circuit switched or packet) must be supported. Packet traffic is characterised by burstiness and variable delay.

New air interfaces based on a single carrier TDMA concept have potential problems to efficiently equalize high bit-rates in "tough" radio environments. Moreover, DS-CDMA systems have a potential problem with small spreading gains for high bit-rate services in the limited spectrum available for UMTS. In this light, we have studied the possibility to base a new air interface on a Multi-Carrier (MC) technology, often referred to as Orthogonal Frequency Divided Multiplexing (OFDM).

III. OFDM AS MULTIPLE ACCESS CONCEPT

The shown interest for the OFDM technique during the past years indicate interesting qualities as stated in [4][5][6][7]. According to results from different activities the most beneficial properties with the OFDM concept, from our point of view, are:

- Each transceiver will have access to all subcarriers within a cell layer (this enable very high bit-rates).
- There is more or less no need of frequency planning within a cell layer (it is performed with an Adaptive Channel Allocation algorithm).
- The technique will handle packet data services and mixtures of packet and circuit services.
- The subcarrier modulation is performed with a Fast Fourier Transform (FFT) which is a well known algoritm and should be considered as a compact digital modulator (easy to implement).
- The division of the spectra to a large number of narrow banded, flat fading channels allow easy equalization even in environments with severe delay spread.
- The division of the signal to a large number of more of less independent channels will provide the flexibility needed for all foreseen future multimedia services (variable bit rate with different quality of services).

Potential drawbacks with OFDM as a multiple access concept are mainly based on that OFDM is a relatively young technique and there are open issues where still no optimum solution has been found. Topics which still are under active research are:

- A tight synchronisation in time and frequency are needed for the system to stay orthogonal. This is a problem essentially on the uplink. Studies has shown that there are methods for handling these types of problems [8].
- The high dynamics of the broadband signal implies a need of a wide range linear power amplifier (note that this is a general problem applying on all broadband systems).

OFDM is a spectrum efficient multiplexing technique that has proven functional in other concepts and standards as [1][9][10]:

- High performance modem for copper wire, twisted pair (ADSL and VDSL).
- High quality audio broadcasting. (DAB, Digital Audio Broadcasting)
- Broadcasting HD-TV.

In general it can be said that uncertainties concerning OFDM as a multiple access concept concerns the system uplink. The main issue is to keep the mobile synchronised to the base stations time and frequency grid. This means that the mobiles must transmit the information with some timing advance due to the different propagation delay of the radio channels. The mobiles need to be synchronised to preserve the system orthogonality and avoid inter channel interference (ICI).

The downlink follows the same paths as the broadcast concepts and has already proven functional. Because all users are multiplexed in the base station they are always orthogonal to each other. If a mobile loose the synchronisation on the downlink, the only thing that happens is that the connection is lost. No other user will suffer from this type of failure.

IV. BASIC PARAMETER CHOICE

One way of looking at OFDM is that it creates a time and frequency grid where each rectangle is orthogonal to all other rectangles in the grid, as shown in Figure 1. The size of a rectangle will depend on the choice of parameters for the OFDM system.

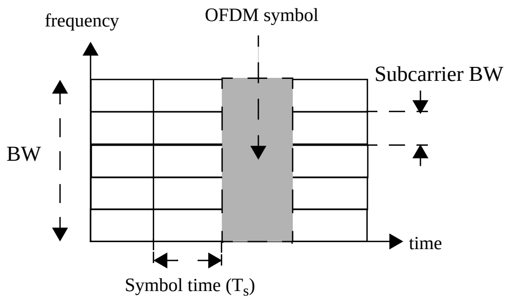

Figure 1: OFDM time and frequency grid

The system concept utilises 1024 subcarriers with a bandwidth of 5 kHz respectively. This gives a total system bandwidth of ~ 5 MHz which corresponds to the assumptions about frequency licensing in Section II. The subcarrier bandwidth of 5 kHz gives a symbol duration of 200 µs which is much greater than the maximum delay spread of the channel. This gives that the subcarriers can be viewed as flat fading, and are easy to equalise.

The slow decay of the sinc-function in the frequency domain, implies that there is a need of large guard bands between operators / cell structures. These guard bands can be reduced by the use of pulse shapes[11]. When the signal is shaped with a Hanning window before transmission, it can be shown that the decay of the sidelobes are proportional to $1/f^3$ compared to the original Sinc-function (~1/f). Unfortunately the pulse shaping breaks orthogonality on every other subcarrier and the maximum bit rate in each cell is reduced by a factor of two. The system capacity is however not reduced, depending on the significantly reduced size of the guard band needed between the cell layers.

The choice of modulation technique for this type of system is still an open issue. A traditional approach is to use some standard modulation as QPSK. Later research has however shown promising results in system robustness for different types of fading channels. This robustness is achieved by increasing the signal constellation in combination with a more powerful coding scheme [12]. As this method looks promising more work has to be done before a modulation scheme is chosen.

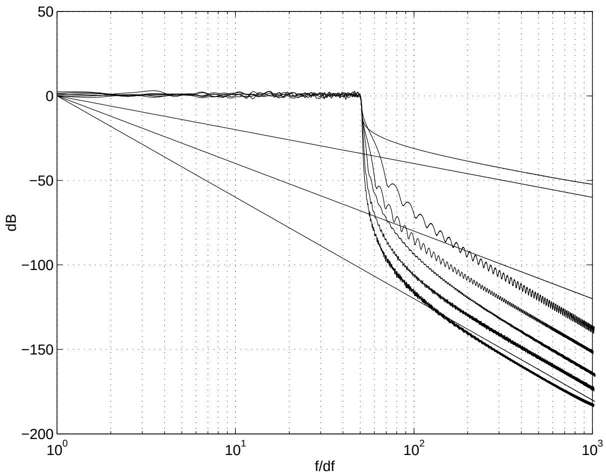

Figure 2: OFDM spectra with different pulse shapes, reference lines are f^{-1}, f^{-2} and f^{-3}.

V. SYSTEM PARAMETERS

On a higher level, system aspects must be taken under consideration. At this stage it is also important to treat the two different transmission paths, downlink and uplink, separately. On the downlink all mobiles can utilise the same pilot signal for channel estimation and time/frequency synchronisation. All information is multiplexed in the base station before transmission and are consequently orthogonal. The use of a common pilot decreases the overhead used for these kind of signals compared to the uplink.

On the uplink all radio signals travel through different radio channels. This implies that all mobiles need to transmit some kind of pilot signal together with its information so that the base station are able to estimate the radio channels and synchronise the mobiles. Due to the many different channels the structure of the pilot symbols must be different on the uplink than on the downlink.

From a diversity point of view it is preferable if the information is separated as much as possible in time and frequency. This because of a fading dip in the radio channel will then only destroy a small amount of data, which might be corrected with Forward Error Correction (FEC). This approach is implementable on the downlink when the data is multiplexed before transmission, in the base station. On the uplink however, the multiplexing is performed in the air, before the signal is received in the base station. This gives that data transmitted from different mobiles will have travelled through different radio channels. It is then preferable if the information from each mobile are placed close connected into “blocks” in time and frequency so that it is possible for the base station to utilise the correlation properties of the radio channel for channel estimation. Known symbols (pilots) are used to estimate the channel and the closer the symbol is to the pilot symbols, the better estimate. It is also preferable to keep information together from a system interference point of view. When information from the same user are kept on subcarriers beside each other they utilise exactly the same timing and orthogonality is maintained within the block, thus lowering the inter channel interference.

The alternative to pilot signals is to use differential encoded data for transmission. This method reduces the channel estimation problem but does not solve the synchronisation problem. The use of differential modulation also makes the symbol errors bursty, lowering the system performance with typically 3 dB.

The size of the blocks is a system design question. It is depending of the parameters diversity, maximum delay and bit-rate granuality. To utilize diversity and achieve good performance the information should be transmitted on different places in the time/frequency grid so that not all information is lost in a fading dip. This method utilises the channel diversity. Unfortunately this is in contradiction of keeping the information together so that channel estimation can be performed (as discussed in the previous section). The result must therefore be a trade-off. The principle of the structure is illustrated in Figure 3.

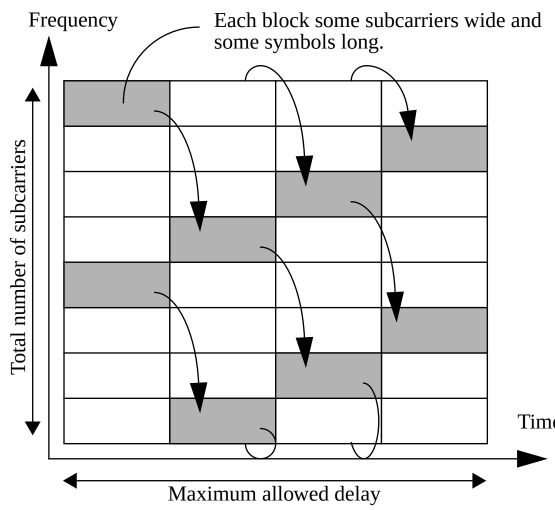

Figure 3: Example of block structure.

If we make the assumption that the radio link must not cause any more delay than about 10 ms, and that the application needs some kind of bit-rate granuality, a suitable size of the blocks can be calculated. All services must from now on use bit rates that are multiples of this basic transmission scheme. Note that if a service does not depend on the maximum delay parameter, it can utilise a transmission speed that is lower than the single block speed, by simply use some kind of time division, transmitting on perhaps only every second block.

Frequency planning can be made obsolete if an adaptive channel allocation (ACA) algoritm is used. This algoritm tries, during a predefined time interval, to estimate the interference on all subcarriers and place the traffic channels on the subcarriers with least interference. The predefined time interval must be a multiple of the time of the block structure. An alternative method than using an ACA-algoritm, is to place every user randomly in time and frequency and use an error correcting code to correct the random errors. Which method to use (ACA vs. FEC) is from a performance point of view not a trivial issue, and the question remains open.

VI. FURTHER WORK

As OFDM is a rather new technique, there are still open issues left to investigate. The use of an adaptive channel allocation algoritm versus a random frequency hop must be investigated. Next, the size of the blocks and the placement of the pilot symbols are topics for further studies. Synchronisation issues on the uplink in combination with a pilot signal that also can be utilised for channel estimation is also an important problem. Recent work has shown methods to increase the robustness of the system for different kind of fading channels by increasing the symbol constellation in combination with a more powerful coding scheme[12].

VII. CONCLUSIONS

A third generation mobile communication system can not be optimized for the speech service. The existing GSM system in combination with DCS 1800 will cover all future need of such a service. The future multimedia services in the fixed network will however create a demand for similar services in the mobile networks.

This paper has pointed out that the key issues for a new air interface in UMTS is to in a flexible way support high and variable bit rate in though radio environments. OFDM shows potential to do this with a spectrum efficient multiplexing of the users and support of high and variable bitrate in though radio environments.

A proposed OFDM concept has been discussed from a general point of view addressing the potential advantages and drawbacks of the system. It should be noted that some open issues still remain regarding OFDM as a multiple access concept, because of the rather new technology.

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