Radio Link Layer Design for IST MATRICE Project

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ABSTRACT

Future trends in telecommunications will converge on delivering broadband IP based applications to the end user, at any time, any place. The need for low cost communications, and the scarce radio spectrum resources has provided the impetus for the MATRICE (Multi-carrier CDMA Transmission Techniques for Integrated Broadband Cellular Systems), which is seen as a potential candidate for beyond 3G cellular communications. This project forces new challenges in the design of the radio access network, in this paper we propose to address these challenges and provide a step towards a layer 2 solution, that can validate the feasibility of MC-CDMA as a potential new air-interface.

I INTRODUCTION

In MATRICE, we will propose to carry out a feasibility study of MC-CDMA to support broadband services, in particular at Layer 1 and 2. The design methodology will follow through from a software perspective towards the implementation of a hardware demonstrator to consolidate the feasibility study, to ensure that the optimality of the algorithms are based on both performance and complexity. Figure 1 shows the outputs of the MATRICE project.

Figure 1: MATRICE Work Package (WP) Structure

In this paper we will address WP4, the radio link layer. In particular providing initial solutions for radio resource control, error control and the MAC layer within an MC-CDMA environment. An evaluation tool will be designed and developed, that will support the performance evaluation of the Radio Link Layer (RLL) mechanisms to provide an initial feasibility analysis based on the MATRICE defined test scenarios. The current project time frame allows us to define an initial design of the evaluation tool with preliminary functions for the RLL mechanisms. This paper will address these issues, and will highlight the scope for future research over the duration of the project, in terms of enhancing Radio Resource Management (RRM) and Medium Access Control (MAC) layer algorithms with adaptivity in mind. This paper is organized as follows: section II will investigate the design of the system level simulator, which will include an analyses of the proposed RLL algorithms and the MATRICE test scenarios; section III will investigate future research concepts, followed by a conclusion in section V.

II SYSTEM LEVEL DESCRIPTION

The objective of Layer 2& 3 focuses on the design, testing and validation of the Radio Link Control protocols to support an MC-CDMA air interface. The intermediate design will house existing RLL protocols that will provide an initial perception of capacity at system level under the scenarios defined in MATRICE, in the presence of circuit switched services. In the advanced stage, advanced RLL protocols will be validated and integrated into the platform, in the presence of bursty IP traffic. The system level evaluation tool can be described by the RLL protocols and the test scenarios:

A. RRM Control Blocks

Call Admission Control

CAC is performed when a mobile station requests communications, and is performed separately for uplink and downlink. This is especially important if the traffic is highly asymmetric. The principle is to accommodate the new user without having impact on the QoS of the remaining users in the system, with optimal usage of the available spectral resources. Typical evaluation criteria for admission control are call blocking and call dropping. Blocking occurs when a new user is denied access to the system, whilst Call dropping refers to the termination of an existing connection. For packet services, the CAC may delay an incoming connection.

Uplink CAC

In the uplink, the CAC is based on a wideband power-based control scheme, where the new user is accepted by
the uplink admission control if the resulting total received power is lower than the threshold:

\[ P_{\text{total, old}} + \Delta P < P_{\text{threshold}} \]

The total receive power \( P_{\text{total, old}} \) can be explained as:

\[ P_{\text{total, old}} = \sum_x 10^{\left(P_{\text{tx,b},dB} + A_{\text{tx,b},dB}\right)/10} \]

where \( P_{\text{tx,b},dB} \) and \( A_{\text{tx,b},dB} \) indicate the transmission power of user \( x \) to cell \( b \) and the corresponding signal attenuation, in dB, respectively. The relation between total received power and the uplink loading factor \( \Delta \eta \) can be expressed as:

\[ P_{\text{total}} = \frac{N_0}{1 - \Delta \eta} \]

where \( N_0 \) is the background noise power.

We use the derivative method to estimate the uplink power increase \( \Delta P \), due to the new user:

\[ \Delta P = \Delta \eta \cdot \frac{dP_{\text{total}}}{d\eta} = P_{\text{total}} \cdot \Delta \eta \]

In equation (5), the load factor of the new user \( \Delta \eta \) can be obtained as:

\[ \Delta \eta = \frac{1}{W} \cdot \frac{1}{\eta} \cdot \frac{\text{Eb/No}}{\text{Io} \cdot \text{Rb}} \]

where \( W \) is the chip rate, \( \text{Rb} \) is the bit rate of the new user, \( \text{Eb/No} \) is the assumed Eb/No for the new connection and \( \eta \) represents the activity.

**Downlink CAC**

Downlink CAC is based on downlink total transmission power i.e. the new connection is admitted if the new total downlink transmission power does not exceed the predefined target value:

\[ P_{\text{bs,old}} + \Delta P_{\text{total}} < P_{\text{threshold}} \]

where the threshold value is set by radio network planning. The total base station transmission power can be presented as:

\[ P_{\text{bs,old}} = P'_{\text{bs,ctl}} + \sum_{\text{cell}b} P'_{\text{tx,cell}} \]

where \( P'_{\text{bs,ctl}} \) presents the control channel transmission power. The load increase \( \Delta P_{\text{total}} \) in the downlink can be estimated based on the initial power, which in turn is related to the distance from the base station to the mobile and can be determined by the open loop power control algorithm.

**Link adaptation**

In the reference system level simulator, circuit-switched services are assumed. Therefore a power control algorithm is necessary in order to keep a constant link quality and lower interference level. As the MATRICE system is a TDD system, an UL Open Loop Power Control exploiting channel reciprocity and joint detection would to be an efficient link adaptation mechanism. However it requires performance results on the advanced link level chain. Hence, the Closed Loop Power Control (CLPC) will be modelled for the UL and the DL. The CLPC is a combination of an Outer Loop PC and an Inner Loop PC. The Outer Loop PC fixes the signal to interference target based on the average measured BLER in order to achieve the BLER target. The Inner Loop PC performs periodical measurements of the SIR, compares it with the SIR target and adapts the transmit power to the radio conditions in order to achieve an SIR target value. The performance of such algorithm depends on the accuracy of the SIR measurements. The period of the inner Loop PC is a multiple of the TDD frame period. The PC increments the transmit power with a constant step of \( \pm dP \), in dB.

The real CLPC is not implemented, as it would require the simulator time step to be at least equal to the measurement period. Only the effects of PC on the system capacity are modelled in the reference simulator through a CLPC function. The CLPC function of the simulator models perfect closed loop power control power that is able to compensate for both path loss and shadowing slow variations and that aims at achieving a BLER target.

**Downlink PC**

For each UE, the CLPC function is called with a period of \( T_{\text{pc}} \) much larger than the real PC period, and with large power increments multiples of \( dP \), in order to perform the following actions.

First, the SIR measurement is updated, and then the new transmit power is deduced:

\[ P_{\text{new}} = P_t + (\text{SIR}_{\text{target}} - \text{SIR}) \cdot \]

where \( P_t \) is the old transmit power; \( \text{SIR}_{\text{target}} \) is the target signal to interference ratio; \( P_{\text{new}} \) is the new required transmit power.

Then, \( P_{\text{new}} = \max(P_{\text{min}}, \min(P_{\text{new}}, P_{\text{max}})) \), and \( P_{\text{new}} = \text{Round}(P_{\text{new}}/dP) \cdot dP \). For the reference simulator \( P_{\text{min}} \) equals zero and \( P_{\text{max}} \) equals the maximum BS transmit power.

Before allocating the new transmit power, the BS total transmission power \( P_{\text{tot}} \) is computed. Then, if \( P_{\text{tot}} + P_{\text{new}} > P_{\text{max}} \), then \( P_{\text{new}} = P_t + P_{\text{max}} - P_{\text{tot}} \) (in linear scale). If \( P_{\text{tot}} + P_{\text{new}} - P_t < P_{\text{max}} \), then \( P_{\text{new}} = P_t + P_{\text{max}} - P_{\text{tot}} \) (in linear scale). Finally, the new transmit power is allocated to \( P_t \).

**Uplink PC**

For the UL power control, the only difference is that \( P_{\text{min}} \) is the minimum UE transmit power (equal to zero for the reference simulator) and \( P_{\text{max}} \) is the UE maximum transmit power. The CLPC loops of different UEs are unsynchronized so as to achieve an accurate SIR estimation. The period \( T_{\text{pc}} \) of the CLPC function is chosen so that:

- \( T_{\text{pc}} \) is much larger than the fast fading coherence time, in order to keep the modelling of such phenomenon at the link level.
- Tpc is lower than the coherence time of the shadowing and path loss, so that these quantities can be assumed constant during a Tpc period.
- Look-up tables provide BLER vs SIR.

Fast power control or pre-distortion techniques can be taken into account in the CLPC function without lowering the measurements period Tpc. This can be taken into account through look-up tables and average power raise in function of the service the environment and the UE's velocity.

Handover
The duplex mode being the TDD mode, the handover algorithm is a mobile assisted hard handover. The UE monitors the received power of other base stations while keeping the old link. When measured power from any monitored base station is higher than the old link by a predefined hysteresis value, the UE will handover to the new base station. The signaling procedure will be ignored in the reference simulator by assuming the signaling will be perfectly accurate and without any delay. For hard handover, the value of hysteresis is very important in that a low hysteresis value introduces too many handovers whereas a high hysteresis results in handover delay hence deterioration of link quality. A good trade-off therefore has to be addressed.

B. MAC Control Block
Dynamic Channel Allocation (DCA)
The dynamic Channel Allocation module will assign radio resources to existing connections. In the first phase, two different types of connections (?) will be assumed: well-defined constant bit-rate connections, with arrival times following a Poisson distribution, and bandwidth-limited random traffic.

The DCA will have to provide a solution to the resource utilization problem: given a set of radio link capabilities \( S \), variable in function of the number of users \( N \), define the link capacity to allocate to each user \( x \), and translate this in system degrees of freedom, namely codes (C), frequencies (F) and time-slots (Tj). Thus the DCA will provide:

\[
\text{opt} \{C, F, Tj\} = f \{N, ?, S\}
\]

where \( S = f \{N, \{x\}\} \). The function \( S \) will be a higher level view of the link-layer behaviour. It will condense average link behaviour as a function of the different link-layer parameters, and in function of the number of users. S can be naturally represented by a normalized table, as shown by table 1.

<table>
<thead>
<tr>
<th>N users</th>
<th>BW (S)</th>
<th>Link parameters ( {C, F, Tj} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I</td>
<td>{1, f_1, T_1}</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>{C_i, f_i, T_i}, {C_j, f_j, T_j}</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>k</td>
<td>{C_n, f_n, T_n}, {C_k, f_k, T_k}</td>
</tr>
</tbody>
</table>

Table 1

Naturally, for each possible combination, S represents the maximum system capacity possible for that number of users. The information for translating each point of this function on to the specific link parameters is then used by the low-level operation of the DCA algorithm.

The high level operation of the DCA will define the optimum channel allocation for each user. This optimum will be exploited in function of the multiple measures: the percentage of users unable to achieve a call, the total achieved bandwidth allocation in function of the total requested, and the percentage of users. As the DCA will also include a time dimension, the variation of user bandwidth along time will also be a parameter.

The simulation entity DCA will allow the evaluation of multiple specific algorithms (such as Best Channel Available, or First Channel Available) in function of these multiple factors, for the specific MC-CDMA link characteristics. However, in the first phase, the traffic is assumed to be equal to all users. This restriction will be waived when much more complex algorithms are developed in the second phase, with IP-oriented DCA algorithms.

C. Link Level Interface
Interface between System Level and Link Level
To provide a truly optimised system level simulator, a detailed definition of the physical layer interface is required, that translates to specific knowledge of the system attributes on a real time basis. Ideally, on-line interaction between with the physical layer and the system level is necessary that takes into account all degrees of freedom that are present (e.g. each users mobility, service requirements, channel conditions, etc..); this is achieved by appropriate interfacing, that translates the system level parameters to optimised physical layer attributes, and vice-versa. This idealistic scenario remains an unreachable target, but we can approximate this interfacing by an ‘average value method’. This technique is a common way of integrating the RAN layers, by obtaining statistics of the SIR to BLER performance over the measurement period. The assumptions are that we have only slow power control to maintain the link quality, and the time granularity of the simulator permits several fading wavelengths, under the mobility conditions defined in the test scenarios. The interference is also assumed to vary at the slow fading rate. This scheme is sufficient to evaluate system load, from a radio perspective, where we assume several MAC frames between the simulator sampling times.

In the advanced stage, a more sophisticated interfacing scheme will be employed based on [1], this will allow improved modelling of the interference variations at the system level. The granularity of the simulator will support preferential treatment to each MAC frame.

D. Test Scenarios
To test the validity of the simulator, the following test environments are assumed, expressed in terms of the test environment description, deployment model, associated mobility model and the propagation model. The shadowing model and the traffic classes used are also given. These are default models proposed in [2]. However, the MATRICE project goes on searching for new propagation models.
available at 5GHz and may update the proposed values of the parameters of shadowing and path loss models.

**Indoor close area environment at 3km/h**
- The indoor deployment model and mobility model are based on the "indoor office test environment" model from [3].
- For the Indoor environment, we use the following path loss formula, that has been modified to support a 5GHz carrier frequency:

\[
L = 106.42 + 20 \log \left( \frac{d}{km} \right) + 3.4k + \left[ \frac{1}{k_{w1}} + a \right] \left[ \frac{1}{k_{w2}} + b \right]
\]  

(10)

where \(d\) is the mobile station to base station distance, \(k_{w1}\) is the number of penetrated thin walls, \(k_{w2}\) is the number of penetrated thick walls.

**Urban environment at 10km/h**
- The urban environment model is based on "the vehicular test environment" derived from [4].
- The cell radius is 300 m. The deployment scheme is assumed to be a hexagonal cell layout. Omni-directional cells will be assumed.
- The mobility model for the Vehicular Test environment is a pseudo random mobility model with semi-directed trajectories. Mobile’s position is updated according to the de-correlation length, and direction can be changed at each position update according to a given probability. Direction can be changed within a given sector to simulate semi-directed trajectory.
- For urban environments, we use the following path loss model:

\[
L = 136.51 + 37.6 \log_{10} \left( \frac{d}{km} \right)
\]

(11)

where \(d\) is the mobile station to base station distance

**Rural environment at 60km/h**
- For the rural environment, we will model a train environment: cells are regularly deployed on the railway. We have assumed that the case of rooftop-to-rooftop propagation mechanisms shall be assimilated to a rural environment when the transmitter antenna has a gain superior to 7 dB. This environment is deduced from the propagation model defined within the IST MIND project [5]. We assume inter-site distance of 3km and omni-directional cell.
- The mobility model for the rural environment is a train environment. Users will be uniformly distributed on the train, and will be moving at a constant speed.
- For rural environments, we use the following path loss model:

\[
L = 114.6 + 33.77 \log_{10} \left( \frac{d}{km} \right)
\]

(12)

where \(d\) is the mobile station to base station distance

**Shadowing model**

The received power is slowly time varying due to shadowing effects. This effect is taken into account in received power calculation by multiplying the transmit power by a random lognormal variable. The log of the shadowing variable is Gaussian with zero mean and variance \(\sigma\) in dB. The shadowing effect is correlated in distance. Therefore the values of the shadowing variable for two positions of the mobile station separated by \(\Delta x\) are correlated.

\[
L_s[dB] = R \times L_{s,0} [dB] + \sqrt{1 - R^2} \times X[dB]
\]

(13)

where \(L_s[dB]\) = Shadowing value at time \(t\); \(L_{s,0} [dB]\) = Shadowing value at time \(t-\Delta t\); \(X\) is a log-normally distributed random variable with standard deviation equal to \(\sigma\); \(\Delta x = d_{cor}/v\); where \(v\) is the user’s speed; \(d_{cor}\) = The de-correlation length.

Table 2 shows the shadowing parameters for the predefined test environment

<table>
<thead>
<tr>
<th>Environment</th>
<th>Shadowing length (d_{cor})</th>
<th>Shadowing standard deviation in dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>5 m</td>
<td>12 dB</td>
</tr>
<tr>
<td>Urban</td>
<td>20 m</td>
<td>8 dB</td>
</tr>
<tr>
<td>Rural</td>
<td>50 m</td>
<td>6 dB</td>
</tr>
</tbody>
</table>

**Table 2**

**Traffic Classes**

A user of the Beyond 3G system shall use two types of applications: real time services that require low delays, and non real time services. Even if IP transport is assumed in the core network, we assume that some mechanisms in future core networks will enable to provide real time services on IP. We assume that the Beyond 3G system will provide at least the four UMTS QoS classes: the interactive QoS class, background QoS class, conversational QoS class, and the streaming QoS class. We assume that real time services will be mapped onto the Conversational QoS class (real time services with very low delay constraints) and the Streaming QoS (real time services with larger delay constraints like streaming video), while non real time services will be mapped onto the Background (data transfer) and the Interactive QoS class (WWW browsing). The four QoS classes have been defined in [6]

Table 3 summarizes the services that we propose for testing.

<table>
<thead>
<tr>
<th>Traffic Class</th>
<th>QoS Class</th>
<th>DL BER</th>
<th>UL PBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low delay real time services</td>
<td>Conversational QoS class (Real time)</td>
<td>GBR = 1 Mbps</td>
<td>GBR = 384 kbps</td>
</tr>
<tr>
<td>Delay &lt; 50 ms</td>
<td>GBR = 384 kbps</td>
<td>GBR = 1 Mbps</td>
<td></td>
</tr>
<tr>
<td>Large delay real time services</td>
<td>Streaming QoS class</td>
<td>GBR = 2 Mbps</td>
<td>GBR = 384 kbps</td>
</tr>
<tr>
<td>Delay &lt; 300 ms</td>
<td>GBR = 384 kbps</td>
<td>GBR = 2 Mbps</td>
<td></td>
</tr>
<tr>
<td>Non real time service</td>
<td>Interactive QoS class</td>
<td>GBR = 384 kbps</td>
<td>GBR = 2 Mbps</td>
</tr>
<tr>
<td>Delay constraints</td>
<td>GBR = 384 kbps</td>
<td>GBR = 2 Mbps</td>
<td></td>
</tr>
<tr>
<td>Non real time service</td>
<td>Background QoS class</td>
<td>GBR = 384 kbps</td>
<td>GBR = 2 Mbps</td>
</tr>
<tr>
<td>Delay constraints</td>
<td>GBR = 384 kbps</td>
<td>GBR = 2 Mbps</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3**
Where GBR is the Information Guaranteed Bit Rate PBR and PBR is the Peak Bit Rate. For the reference system level simulator, circuit-switched services of 384 kbps, 2 Mbps and 10 Mbps will be tested.

III ADVANCED SIMULATOR

The advanced algorithms will be stabilised by the end of the second year. In the MATRICE project, we intend to investigate the following concepts.

CAC
To design and specify advanced CAC for packet-based services, so as to optimise the grade of service for the specific MATRAVE environments.

HO
To consider soft handover for TDD MC-CDMA in the case of delay constrained data. To investigate the possibility of interaction between CAC with both resource allocation and mobility prediction to achieve this aim. To consider the performance of the UTRA HO algorithm in the presence of MC-CDMA with adaptivity in mind.

Link Adaptation
For non real time services, the system throughput is maximised with a best effort strategy. In this case, AMC and H-ARQ is a more efficient link adaptation mechanism than power control. With packet services, the traffic is very bursty, therefore the system level simulator must take into account fast fading variations, which leads to a very low time step for the simulator. In this case, a packet level simulator is necessary. In the advanced simulator, we will evaluate AMC and ARQ mechanisms that jointly work with packet scheduling and DCA.

IP interface
To develop IP transport blocks that take into account QoS support and mobility management. This will provide a packet stream to feed the radio layer. This packet stream will be fed periodically to the Advanced DCA algorithm to provide the packet population it will use for channel decisions.

Advanced Dynamic Channel Allocation algorithms
To enhance channel throughput in the presence of bursty traffic. These algorithms will periodically operate on the packet population at its input, and perform channel allocation based on this. The algorithms will implement two different strategies, with different computing complexity; a first strategy for defining an optimum, assuming traffic statistics are known (and thus inside knowledge on the types of packets are known); and minimal knowledge, where pending packets will be treated simply as a packet population and decisions will be made on “instant” statistics.

IV CONCLUSION

This paper has considered the design of the dynamic system level simulator within the MATRICE project. It has highlighted the role of WP4 within the MATRICE framework, its interactions and the main outputs. The description of the system level simulator provides an initial solution to the design of an RLC layer to support an MC-CDMA air-interface, based on the RRM and DCA. Moreover, a definition was given of the MATRICE test scenarios, in terms of mobility, deployment models, pathloss at 5 GHz, the assumed traffic classes and a model for correlated shadowing. Table 4 provides a summary of the simulator attributes for the intermediate and advanced definition. Finally, the future research topics focused on advanced RRM and DCA were addressed.

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Reference V.1</th>
<th>Advanced V.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Interface</td>
<td>MC-CDMA</td>
<td>MC-CDMA</td>
</tr>
<tr>
<td>Duplex Mode</td>
<td>TDD</td>
<td>TDD</td>
</tr>
<tr>
<td>Synchronization Error</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Services</td>
<td>Circuit Switch</td>
<td>Packet</td>
</tr>
<tr>
<td>Mobility</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Fast Fading</td>
<td>Via Interface</td>
<td>YES</td>
</tr>
<tr>
<td>Interference Modelling</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Traffic Models</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Path Loss</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Slow Fading</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>RRM algorithms</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Packet Retransmissions</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Receiver Performance</td>
<td>Via Average Value Interface</td>
<td>Via Actual Value Interface</td>
</tr>
</tbody>
</table>

Table 4: Simulator Attributes

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[3] ETSI, "Unival Mobile Telecommunication System (UMTS); Selection procedures for the choice of radio transmission technologies of the UMTS (UMTS 30.03 version 3.2.0)" TR 101 112 v3.2.0, April 1998.