Usage of Link-Level Performance Indicators for HSDPA Network-Level Simulations in E-UMTS

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***Abstract* - This paper describes integration of HSDPA (High-Speed Downlink Packet Access) link-level simulation results into network-level simulations for Enhanced UMTS. The link-level simulations model all physical layer features depicted in the 3GPP standards. These include generation of transport blocks, turbo coding, rate matching, spreading, scrambling and modulation. At the receiver side, all complementary blocks were designed, with soft-decision demodulation, and a turbo decoder using the MAP (Maximum A Posteriori) algorithm with 8 iterations.**

An analytical formula is defined that fits the CQI-dependent (Channel Quality Indicator) BLER (Block Error Rate) versus Eb/No results in an AWGN (Additive White Gaussian Noise) channel. This formula models the physical layer in the network-level simulator. A further extension for frequency selective fading channels has been defined.

The network-level simulator includes propagation models that provide SNR values. Based on these SNR values and the simplified physical layer model, an algorithm selects the CQI, and determines the actual BLER at time of reception. The rounding down and delaying of the CQI reporting, which corresponds to the W-CDMA standard, has a significant impact on throughput and transfer delay of the HS-DSCH. Some compensation can be found in a modified transmission.

The integration of the link-level and network-level simulators described in this paper give accurate and realistic results that can next be used in more studies that focus on network layer aspects of packet based services over HSDPA.

Keywords – UMTS, HSDPA, Link Adaptation, CQI, TBS, link-level simulation, network-level simulation

I. Introduction

While UMTS is still in its initial deployment phase in Europe, researchers are investigating improvements to the system's performance. A key improvement is realized in HSDPA, which is defined for release 5 of the 3GPP (3rd Generation Partnership Project) UMTS standard. HSDPA aims at increasing both the systems capacity as well as the users' peak throughput for data services. The maximum bit-rate increases from 2 Mbps to over 10 Mbps. Work in the area of mobile cellular systems operating in multiple services and multiple rates is in a pioneering phase and therefore an interesting topic for the current research community.

This paper reflects part of the work done within the IST project SEACORN [7], which is executed by a European consortium. The project aims at creating simulation tools for the study of possible enhancements to the UMTS standards. The work presented in this paper reflects the integration of the results obtained within two SEACORN WPs; one focusing on Wireless Techniques for Capacity Enhancement, the other dealing with Routing and Diffserv.

The link-level simulator implements all physical layer aspects of Enhanced UMTS (release 5) as specified by 3GPP. The enhancements include HSDPA (with both QPSK and 16-QAM modulations), which is the main aspect for the integration with the network-level simulator. The network-level simulator implements a complete connection between applications on UE and core network side. The simulator focuses on MAC (Medium Access Control) and RLC (Radio Link Control), where high-speed versions of these protocols are implemented for HSDPA according to the 3GPP W-CDMA standard, release 5.

Realistic results from the network-level simulator require a model of the physical layer that mimics its main characteristics. It is most important that the model's relative behavior is realistic. An abstracted physical layer model in the network-level simulator is allowed to contain some deviation in absolute sense, as the simulator aims at studying characteristics of network-level functions and procedures.

This paper presents (II) link-level simulation results for HSDPA, (III) an analytical model that represents the physical simulation results, (IV) usage of the analytical model for generation of CQI and BLER in a network-level simulator, and (V) some results obtained with the model.

II. HSDPA Link-Level Results

Power control is typically used in UMTS. HSDPA uses link adaptation instead. The variation in channel conditions is taken care of through the use of different orders in the modulation and different coding rates. On its turn, these define several Transport Block Sizes (TBS), alongside different User Equipment (UE) types [3]. The UE reports the observed quality to the Node-B (Base Station) by means of a Channel Quality Indicator (CQI). The Node-B decides, based on the CQI and additional information, such as the amount of available data to send, what TBS to use in its transmission. Large TBSs require several channelization codes to be allocated to the High Speed

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Downlink Shared Channel (HS-DSCH). E.g. the largest TBSs require 15/16 of all channelization codes of a cell to be allocated to the HS-DSCH. This may conflict with guarantees of QoS to other services, using DCHs. When a UE reports a high quality level, the Node-B may also decide to use a smaller TBS with less power allocated.

A link-level simulator estimates the performance of each single TBS. The simulator considers radio communication between the Node-B and the UE using the HS-DSCH, and follows the 3GPP specifications. The simulations assume a Rake receiver. This type of receiver employs Maximal Ratio Combining (MRC) to all paths it can retrieve. A searcher function in the Rake receiver determines the delays of the multipath components in the signal. By adding these components after multiplying them with the complex conjugate of the channel estimation, results in a MRC addition of the signals, which equals regaining all received power.

The resulting complex conjugate estimates of the signal undergo descrambling and despreading operations. The demodulator generates (for QPSK and 16-QAM) soft information values for the bits, without quantization, to be used in the turbo decoder. The turbo decoder uses the MAP algorithm, with 4-8 iterations (controlled by CRC checks).

The channel estimation uses the Common Pilot Channel (CPICH) and a sliding window filter with a length of 16 symbols. The simulation assumes the CPICH power to be equal to the power level of the DPDCH. The CPICH consists of 30 symbols per frame, which are spread with a Spreading Factor (SF) of 256.

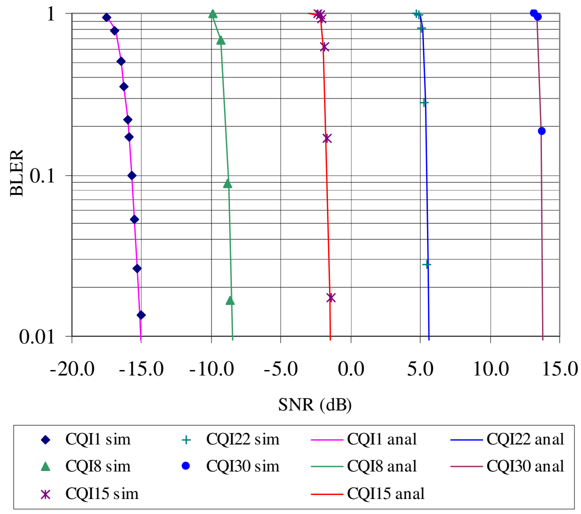

Fig. 1 – BLER versus SNR AWGN link-level simulation results and the analytical approximation (sim = simulation; anal = analytical model)

The selection of this filter length materialized into a good performance for all considered channels and speeds. The filter length relates to the short duration of the HSDPA TTI of 2 ms. Speeds of 3 km/h through 120 km/h cause limited channel variations within a single TTI. To enable statistically valid simulation results, a Monte Carlo method was used to estimate the BER as well as the BLER. All link-level results provide an estimate with an error of less than 1%. Fig. 1 presents the simulator's link-level results for AWGN for a selection of CQIs (symbols in Fig. 1). Consecutive CQIs have a nearly constant offset of 1 dB at a BLER of 10% [4]. The simulations have been performed only for a subset of all possible TBSs, but do reflect the overall behaviour.

III. Analytical Model for Block Errors

The link-level results provide, for a subset of all possible CQIs, a limited number of points on each Eb/No versus BLER curve. A full coverage of all possible combinations of CQI and Eb/No is not realistic due to its computational load and is not necessary for the purpose of this study. The network-level simulator however requires a reasonable estimate of the relation between Eb/No and BLER for each CQI and a much larger number of points on each curve. This will be generated using interpolation.

The TBSs selection in HSDPA targets a 1 dB step size in SNR in AWGN channel conditions for a BLER of 10%. So a formula for interpolation is likely to be based best on SNR. Based on Fig. 1, the SNR is likely to have a near linear relation to the CQI for a BLER round 10%.

No trivial formula fits the complete range of results. An analytical formula fitting the simulation results with a RMSE of 0.1 dB is found to be:

$$SNR = \frac{\sqrt{3} - \log^{10}(CQI)}{2} \cdot \log^{10}(BLER^{-0.7} - 1) \ldots \\ + 1.03 \cdot CQI - 17.3 \qquad (1)$$

Fig. 1 shows the result of this formula in combination with the simulation results from the link-level simulations. The figure shows the near perfect match.

Inside the network-level simulator the UE indicates the CQI to the Node-B. The CQI represents the largest TBS resulting in a BLER of less than 0.1. Equation (1) provides the relationship between BLER, CQI and SNR. There is however no closed form solution to express the CQI as function of BLER and SNR. For simplicity in the simulator, the relation between CQI and SNR for a BLER of 0.1 is approximated through a linear function, based on 3GPP standard [3]:

$$CQI = \begin{cases} 0 & SNR <= -16 \\ \left\lfloor \dfrac{SNR}{1.02} + 16.62 \right\rfloor & -16 < SNR < 14 \\ 30 & 14 <= SNR \end{cases} \qquad (2)$$

The RMSE of this approximation is less than 0.05 dB, based on integer CQI values. Recall that a CQI equal to 0 indicates out of range and the maximum CQI equals 30. So the function truncates at these limits.

This AWGN-based model can only be applied to a channel as long as the fading is frequency non-selective. This implies that the frequency response of the channel is nearly flat over the bandwidth of the channel. Frequency selective fading disperses the signal over time and results in Inter Symbol Interference (ISI). When applying a Rake receiver, moderate frequency selective fading is beneficial to the signal quality, as it provides frequency diversity. Excessive frequency selective fading however degrades the signal quality.

The degradation relates to the SNR, channel coding and modulation. Higher modulation schemes are more sensitive to frequency selective fading. Physical layer simulation results show that frequency selective fading improves the performance for QPSK, due to the reduction of deep fades, while it deteriorates the performance for 16-QAM due to ISI.

To model the impact of frequency selective fading, the symbol time of the non-spread signal is considered as primarily the interference between data symbols is of interest. This takes implicitly into consideration modulation and channel coding.

With a SF of 16 and WCDMA chip rate of 3.84 Mcps, the HS-DSCH symbol time is 4.17 µs. The adapted model uses the symbol time. Power received in one finger, becomes interference to another finger proportional to the difference in delay between the fingers, expressed in symbol time. A fraction of the received power changes from wanted signal into unwanted ISI.

The MRC like Rake receiver multiplies the signal by the complex conjugate of the channel estimate. Assuming perfect channel estimation, this corresponds to multiplying with the SNR of each finger. The fraction of the power that becomes interference can now be expressed per finger. When there are N fingers that each have a power p_i, a delay δ_i and a symbol time equal to τ, the fraction of the power of finger n that becomes ISI at time t, equals:

$$isi_{t,n} = \frac{\sum_{i=1}^{N} p_{t,i} \cdot \frac{|\delta_i - \delta_n|}{\tau}}{\sum_{i=1}^{N} p_{t,i}} \quad (3)$$

The resulting SNR at given time t as a result equals:

$$SNR_t = 10 \cdot \log^{10}\left(\frac{\sum_{i=1}^{N} p_{t,i} \cdot (1 - isi_{t,i})}{\sum_{i=1}^{N} p_{t,i} \cdot isi_{t,i} + n}\right) \quad (4)$$

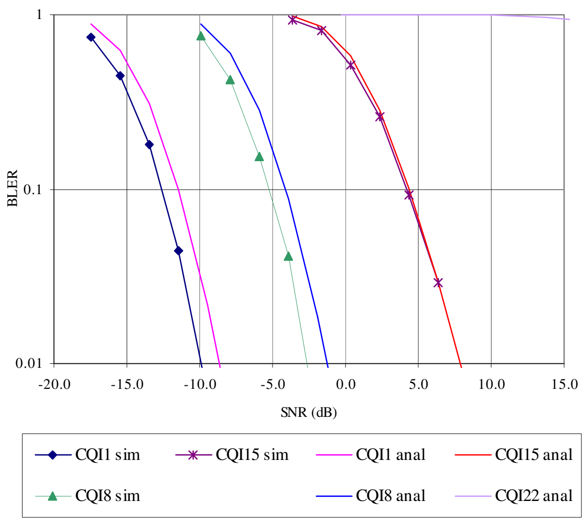

Fig. 2 – BLER versus SNR link-level results and the analytical approximation in a Vehicular A channel (sim = simulation; anal = analytical model)

The calculated fraction $isi_{t,n}$ is time dependent as the ration between the powers is time dependent. A time invariant estimate isi_n can be found by taking the power profile of the channel instead of the powers. In order to tune the results for more realistic mimicking, a real implementation of the Rake receiver, the symbol time τ should be reduced. This amount depends on the sensitivity of the receiver to ISI. The analytical model matches the physical layer simulation results, when τ was set to 0.3 times the true symbol time. This value was found to give satisfactory results for both QPSK and 16-QAM, where ISI reduction techniques were applied to the 16-QAM receiver. Fig. 2 compares the relation between BLER and SNR for the analytical model to detailed link-level simulation results. The error in SNR is clearly larger for this case than for the AWGN case. The low CQI values contain a 1 dB error. The result for CQI 15 is nearly perfect. For high CQIs the Rake receiver cannot cope with the Vehicular A channel. This is also reproduced in the analytical model. It produces an error floor of 0.75 respective 1 for CQI 22 and CQI 30.

IV. CQI and BLER Generation

The models provide a translation between SNR, CQI and BLER. The network-level simulation requires a trace of SNR values to determine the CQI. During each TTI the SNR at the UE of a received DL transmission, results in a CQI that the UE reports to the Node-B in the next TTI. Another TTI is required by the Node-B to receive and process the CQI. The Node-B contains an algorithm that combines CQI information alongside information like the amount of data that needs to be transmitted to determine the scheduling and selection of the TBS for the next TTI [3]. Overall, a three-TTI delay exists between the actual SNR condition on which the CQI is based and the transmission of the resulting transport block. The simulator implements this as a simple delay.

The SNR results from the overall path loss and interference. Path loss consists of distance loss, shadow fading and multi-path fading. Without compromising the accuracy of the network-level simulation results, each UE has its own fixed distance to the Node-B, resulting in a fixed distance loss.

The shadow fading has a log-normal distribution, correlated in time. Expressing the shadow fading in dB results in:

$$\mathrm{L}_{\mathrm{sh}}(t) = 2^{-\frac{d_\tau}{D}} \cdot \mathrm{L}_{\mathrm{sh}}(t-\tau) + \sqrt{1 - 2^{-\frac{2 \cdot d_\tau}{D}}} \cdot S \cdot \mathrm{N}(0,1), \quad (5)$$

where d_τ is the distance traveled during time τ, D is the correlation distance, S is the standard deviation of the shadow fading (in dB) and N(0,1) is a normal distributed random value [5]. The values D and S depend on the environment. The shadow fading is added to the fixed distance loss (in dB).

The multi-path fading model assumes usage of a Rake receiver, in line with the discussion in section III. The channel estimation of the Rake receiver is assumed to be ideal, i.e. the time delay and power levels of all signal components are known.

In a flooded WCDMA system, where cells are surrounded by loaded cells, the inter-cell interference level is more or less constant over the complete area, except for the effect of shadowing. As the wanted signal is modeled with shadowing it suffices for network-level simulations to model the inter-cell interference as a fixed power level.

Intra-cell interference is strongly correlated to the wanted signal. From a propagation point of view it has an identical behaviour. The power of the intra-cell interference can fluctuate over time. Capacity control functions in UTRAN will however attempt to utilize the available power as efficiently as possible. The power is balanced between dedicated channels and the HS-DSCH, allocating more to the HS-DSCH when the dedicated channels need less power. As a result the transmission power of the Node-B is roughly constant for systems applying HS-DSCH.

The transmission of channels is orthogonal to all transmissions using the same scrambling code. Frequency selective fading will destroy this property to some extent. A fraction of all DL transmissions turns into interference. For the purpose of the network simulation model it suffices to assume this to be a fixed power level that undergoes the same propagation characteristics as the wanted signal.

The assumptions specified above may introduce small errors in the link-level results, but, as already mentioned in the introduction, this is only effecting the absolute behavior, and not the relative characteristics in time. As the simulator aims at studying characteristics of network-level functions and procedures, it mainly prescribes that the underlying physical model's relative behavior is realistic, which is the case in this study.

V. RESULTS

Fig. 3 shows a sample of the CQI generation process in a 3km/h Pedestrian A channel. The figure clearly shows the delay of three TTIs in the CQI generation, where we note that a HSDPA TTI lasts 2 ms. In addition, the figure shows that the CQI is truncated to integer values.

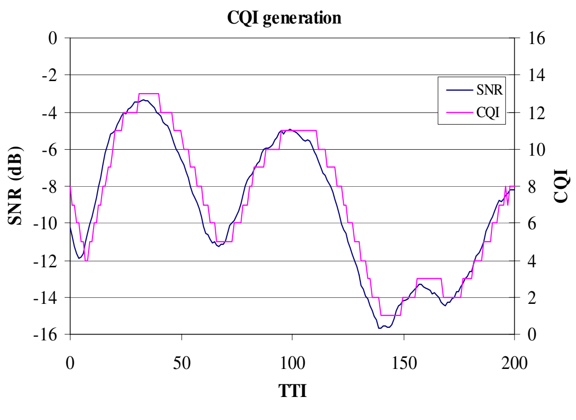

Fig. 3 – Sample of CQI generation in a Pedestrian A environment

As a result of the delay in this CQI generation process, it might happen that a non-optimum TBS is selected for transmission. This effect can clearly be seen from Fig. 4. The figure shows the BLER for each TTI for the same sample trace, based on (1). It is based on the actual SNR and the delayed CQI from figure 3. While the CQI aims at a BLER of 0.1, quite extreme BLER variations can be seen, corresponding to the error in CQI as seen in figure 3. Due to the floor function in (2), the resulting BLER is lower than the target value for most TTIs.

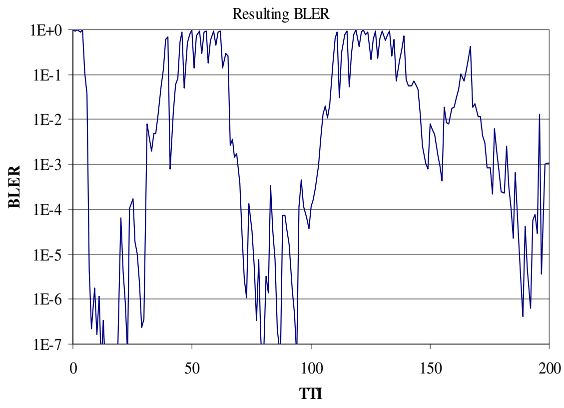

Fig. 4 – Sample of BLER as a result of CQI generation and 3 TTI delay

We next discuss the effect of Hybrid-ARQ. Too low CQIs (with respect to the current channel conditions) result in very low BLERs. This implies that the data is received correctly in practically all cases at the cost of a sub-optimal utilization of the channel. We come back to this trade-off later on in this study. Too high CQIs result in high BLERs. The Hybrid-ARQ process of HSDPA retransmits such packets after a few TTIs. This significantly decreases the BLER due to both the soft-combining of Hybrid-ARQ as well as the high probability that the SNR has changed during the time until this retransmission. In case the data, after three H-ARQ transmissions, still is received in error, the system will fall back to the ARQ functionality in the RLC, which will effect in a much longer delay.

To show the basic characteristics of the CQI reporting process and the Hybrid-ARQ functionality, a number of basic tests have been performed. Table 1 shows the results of these basic tests. The table shows four 'TBS selection algorithms'. These represent:

1. Float CQI, no delay: This is the basic reference case. The CQI is reported as a float (equation (2) without the floor function). The Node-B transmits accordingly as if it has infinite small granularity of the TBSs. The Node-B can use the CQI without delay due to reporting.
2. No delay: The integer CQI (equation (2), now including the floor function) is reported and used by the Node-B, but like 1, without a reporting delay.
3. Standard: The integer CQI is reported and used by the Node-B, now with the normal 3 TTI reporting delay included. This case is the most basic implementation possible.
4. Conservative: The integer CQI is reported. The Node-B contains an algorithm that selects a TBS that corresponds to the reported CQI minus 1.

Note that algorithms 1 and 2 model theoretical limits that cannot be reached in practice.

Table 1 – Hybrid-ARQ performance related to CQI processing in a single Rayleigh channel at 3 km/h. The throughput and delay are reported relative to the reference case algorithm 1.

TBS selection algorithm	Success rate after HARQ transmission #			Through-put	Delay
	1	2	3		
1. Float CQI no delay	0.911	0.997	0.999	1.00	1.00
2. No delay	0.988	0.999	1.000	0.98	0.95
3. Standard	0.791	0.905	0.938	0.71	1.25
4. Conservative	0.936	0.966	0.988	0.74	1.03

Table 1 displays the success rate after each Hybrid ARQ transmission, the throughput relative to the throughput for reference algorithm 1, and the RLC transfer delay relative to that of algorithm 1. The throughput equals the weighted success rate, taking the time evolved, as well as the change in TBS into account. The delay measures the RLC transfer delay, composed from the following delays:

- 6 TTI for each H-ARQ retransmission,
- 20 TTI for each RLC retransmission,
- 10 TTI for each downlink transmission.

This typically results in a average delay of somewhat more than 10 TTIs, *i.e.* 20 ms. Of course the 10 TTI to wait for a transmission should only be taken into account in the delay measure when the actual time between a request for a service and the start of it is important.

It is obvious that for all cases, the success rate should increase during a H-ARQ process. Comparing algorithms 1 and 2 shows that the floor operation increases the success rate after any number of Hybrid-ARQ processes. The floor operation decreases both the throughput and the delay. Algorithm 2 transmits a TBS that is on average 10% smaller than the TBS of algorithm 1. The loss in TBS is compensated by the gain due to the higher success rate.

The comparison of algorithms 2 and 3 shows the impact of the reporting delay. The success rate dramatically drops, as the CQI is somewhat out-dated. Effectively the throughput significantly decreases and the delay increases. The initial probability of success of less than 0.8 should be avoided.

Algorithm 4 does this by decreasing the CQI by 1. The rate of success is closer to the reference cases than algorithm 3 is. As a result the delay is very close to the reference cases. The lowering of the CQI by 1 decreases the TBS by 20%. As a result, the throughput did only increase to a limited extent, disregarding the improved success rate. This basic study shows that gain may be achieved in both throughput and transfer delay through careful selection of the TBS, i.e. CQI.

VI. Conclusions

This paper presents a brief overview of the modeling of link-level results for the purpose of network-level simulations. The link-level simulator produces results of BLER versus Eb/No for an AWGN channel. After correcting for processing gain, the results show the expected 1 dB step between SNRs for a BLER of 0.1 for consecutive CQIs. These results are used for the derivation of an analytical model that expresses SNR in terms of CQI and BLER. This model provides an abstraction of the physical layer suitable for integration into a network-level simulator. The model was extended for frequency selective fading, where part of the transmitted signal is received as ISI.

The paper also shows some examples of how the model materializes the behavior of the Link Adaptation and Hybrid-ARQ processes in HSDPA. The integer value reporting of CQIs and the three TTI delay in the usage of the CQI, results in a significant deviation of the actual BLER compared to the target of 0.1. A conservative approach in selecting the TBS for transmission appears beneficial.

In this study we have described how link-level results form the input for the network-level simulator that will be used for analysis of the end-to-end performance of packet based services over the WCDMA air-interface, which is enhanced with HSDPA. The various features that can be studied with this simulator may include alternatives for fast scheduling [6], RNC – Node-B flow control, and TBS selection. The simulator will also enable studying the interaction between HSDPA and the services it carries [8]. Services that currently are available to the network-level simulator include web browsing, video streaming and bulk data transfer.

Acknowledgments

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