ICT-215282 STP ROCKET

Reconfigurable **O**FDMA-based **C**ooperative Networ**K**s **E**nabled
by Agile Spec**T**rum Use

D12

5D2 - Specification of a reconfigurable MAC/PHY protocol and guidelines for its application

Contractual Date of Delivery to the CEC:	**31/12/2009**
Actual Date of Delivery to the CEC:	**29/01/2010**
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Workpackage:	**5**
Est. person months:	**14.62**
Security:	**Public**
Dissemination Level:	**Public (PU)**
Version:	**1.2**
Total number of pages:	**59**

Abstract:

In this deliverable, different concepts to increase the link and cell capacity respectively are presented. The main focus of the proposed concepts lies on the Media Access Control (MAC) and only partly on the Physical (PHY) layer. The deliverable contains link level as well as system level analysis.

Dynamic adaptation of the ARQ segment size depending on the link quality and reduction of signalling overhead through new ARQ acknowledgement strategies are the main areas of link level evaluations. The investigations show that the benefit of dynamic adaptation of the ARQ segment size is out of all proportion to the increased complexity. On the contrary, the new proposed acknowledgement strategies provide considerable overhead savings in many operating conditions.

Flow control in relay enhanced cells and signalling of resource usage patterns are investigated at system level. A comprehensive set of combinations of flow control and ARQ mechanisms to efficiently provide packet-loss free connections is listed and their advantages and disadvantages are described. According simulation results show that flow control leads to cell capacity gains but mainly in high load conditions. The presented concept for signalling resource usage patterns allows for the efficient realization of spectrum access by mutual observation.

Keyword list: spectral efficiency, link level, dynamic ARQ segment size, HARQ, FEC, flow control, Relay Enhanced Cell (REC)

Executive Summary

High cell capacities up to 1Gb/s are demanded by the International Telecommunication Union (ITU) for future IMT-Advanced systems. This requires the development of advanced techniques to increase the spectral efficiency of the whole system. Thereby, the focus for improvement may be on both - link level and system level. This deliverable addresses both aspects. Link level improvements are presented in Chapter 2 and system level improvements in Chapter 3.

Dynamic adaptation of Automatic Repeat Request (ARQ) segment sizes depending on the current channel quality is investigated in Section 2.2. If the channel suffers from a high error rate Media Access Control (MAC) Service Data Units (SDUs) are segmented into small parts. Thus, if the transmission of one segment was erroneous, only few bits have to be retransmitted. On the other side, if the channel has a low error rate the SDUs are segmented in larger parts to reduce MAC signaling overhead. The results show that only marginal gains can be reached. This does not justify the use of dynamic segmentation as it introduces additional complexity for signaling segment sizes and processing PDUs in the MAC layer.

The section 2.4 focuses on the investigation of management overhead generated by error correction procedures. Firstly, the overhead of stand alone ARQ is analyzed and three versions of potential improvement are presented. The first proposal is based on the conventional ARQ, however only negative NACK is transmitted. The second one provides information on erroneous blocks in form of block sequence numbers. The last one enables to select the best one scheme (out of conventional ARQ, proposal I and proposal II) from the overhead point of view. The selection of the "best" scheme is done on per frame basis. The analysis of all proposed schemes is done for scenario with RSs as well as without RSs. The ARQ proposal III is furthermore evaluated together with HARQ technique. Four combinations of ARQ and HARQ are considered: conventional ARQ & HARQ with and without interaction between both; ARQ proposal III & HARQ with and without interaction. The evaluation is performed over the set of ARQ and HARQ parameters.

The flow control mechanism described in Section 3.1 increases the overall cell capacity of Relay Enhanced Cells (RECs). In RECs PDUs may get lost at Relay Stations (RSs) if the capacity of a connection from the RS to a Mobile Station (MS) is different from the capacity of the connection for that MS from the Base Station (BS) to the RS. A possible solution to avoid PDU loss is presented in the chapter. By avoiding buffer overflows in the DL relay buffer through flow control the carried throughput can be increased up to 10%. The results for the ideal signalling of flow control information show that the increased throughput is reached at the expense of an increased delay. In Section 3.2 a mechanism for the efficient signalling of resource usage patterns is described that enables spectrum access by mutual observation investigated in ROCKET deliverable 4D2.

Table of Contents

References & Standards

[Alvarion2007]	Alvarion : BreezeMAX namuals. Available at: http://www.alvarion.com/products/breezemax/.
[IEEE802.16e]	IEEE P802.16e/D12, “Air Interface for Fixed and Mobile Broadband Wireless Access Systems: Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands”, New York, December 2005.
[Chen2008]	Chen, K.C, De Marca, J.R.B., *Mobile WiMAX*. West Sussex: Wiley&son Ltd, 2008.
[Dinan2007]	Esmael DINAN: „MPLS Backhaul for Mobile WiMAX and LTE“ MPLS 2007 Conference. Washington DC, USA. 2007.
[Hoymann2005]	Hoymann, C., "Analysis and performance evaluation of the OFDM-based metropolitan area network IEEE 802.16." Computer Networks, Vol. 49, pp. 341-363, 2005.
[Hoymann2006]	C. Hoymann, K. Klagges, and M. Schinnenburg, “Multihop Communication in Relay Enhanced IEEE 802.16 Networks,” in Proceedings of the 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Helsinki, Finland, Sep 2006, p. 4. [Online]. Available: http://www.comnets.rwth-aachen.de
[Hoymann2008]	IEEE 802.16 Metropolitan Area Network with SDMA Enhancement, Ph. D. Dissertation, Aachen University, p. 269, ISBN:3-86130-936-X, [Online]. Available: http://www.comnets.rwth-aachen.de
[IST-STRIKE]	EU project IST-STRIKE, http://ist-strike.org
[Kang2006]	Kang, M.-S., Jang, J. "Performance evaluation of IEEE 802.16d ARQ algorithms with NS-2 simulator." Asia-Pacific Conference on Communications, 2006. doi:10.1109/APCC.2006.255785.
[Kliazovich2008]	Kliazovich, D., Tommaso, B., Dalsass, S., Serrelli, F., Redana, S., Granelli,F. "Cross-Layer Error Control Optimization in WiMAX". Global Telecommunication Conference 2008, New Orleans, USA, 2008.
[Krishnamachari2003]	Krishnamachari, S., van der Schaar, M., Choi, S., Xu, X. "Video Streaming over Wireless LANs: A Cross-layer Approach." IEEE Packet Video Workshop, Nantes, France, 2003.
[Lee2008]	Lee, B.G., Choi,S, "Broadband Wireless Access and Local Networks: Mobile WiMAX and WiFi." USA: Artech House. 2008.
[Maheshwari2008]	Maheshwari, S., Boariu, A., Bacciccola, A., "ARQ/HARQ inter-working to reduce the ARQ feedback overhead," contribution to IEEE 802.16m No. C802.16m-08/1142, 2008.
[Martikainen2008]	Martikainen, H., Sayenko, A., Alanen, O., Tykhomyrov, V., "Optimal MAC PDU size in IEEE 802.16." 4th International Telecommunication Networking Workshop on QoS in Multiservice IP Networks, pp. 66-71, 2008.
[NatLab2005]	National Laboratory for Applied Network Research : Iperf-The TCP/UDP Bandwidth Measurement Tool. USA: University of Illinois. 2005. Available at: http://dast.nlanr.net/projects/Iperf/#whatis.
[Provvedi2004]	Provvedi, L. Rattray, C. Hofmann, J. Parolari, S., "Provision of MBMS over the GERAN: technical solutions and performance," Fifth IEEE International Conference on 3G Mobile Communication Technologies, pp. 494- 498, 2004.
[Rocket_D2]	Rocket project deliverable, “Report on Operational Scenarios and Simulation Methodology”.

[Sayenko2008]	Sayenko, A., Martikainen, H., Puchko, A., "Performance comparison of HARQ and ARQ mechanisms in IEEE 802.16 networks." International symposium on Modeling, analysis and simulation of wireless and mobile systems. Vancouver, Canada, 2008.
[Sengupta2005]	Sengupta, S., Chatterjee, M., Ganguly, S., Izmailov, R., "Exploiting MAC Flexibility in WiMAX for Media Streaming." World of Wireless Mobile and Multimedia Networks, 2005, doi: 10.1109/WOWMOM.2005.41.
[Sengupta2008]	Sengupta, S., Chatterjee, M., Ganguly, S., "Improving Quality of VoIP Streams over WiMax." IEEE Transactions on Computers, 57(2), pp. 145-156, 2008.
[Tykhomyrov2007]	Tykhomyrov, V., Sayenko, A., Martikainen, H., Alanen, O., Hämäläinen, T., "Performance Evaluation of the IEEE 802.16 ARQ Mechanism." Next Generation Teletraffic and Wired/Wireless Advanced Networking (pp. 148-161). Berlin: Springer, 2007.
[Wiemann2005]	Wiemann, H.; Meyer, M.; Ludwig, R.; Chang Pae O; "A novel multi-hop ARQ concept", Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st Volume 5, 30 May-1 June 2005 Page(s):3097 - 3101 Vol. 5
[WiForum2009]	WiMAX Forum. WiMAX ForumTM Mobile System Profile Specification (Release 1.5 Common Part), August 2009.

List of abbreviations & symbols

ACID	HARQ Channel ID
AI_SN	HARQ Identifier Sequence Number
ACK	Acknowledgement
ARQ	Automatic Repeat Request
BE	Best Effort
BPSK	Binary Phase Shift Keying
BS	Base Station
CC	Chase Combining
CID	Connection Identifier
CRC	Cyclic Redundancy Check
DL	Down-link
FDD	Frequency Division Duplex
FEC	Forward Error Correction
HARQ	Hybrid Automatic Repeat Request
IE	Information Element
IR	Incremental Redundancy
ITU	International Telecommunications Union
LTE	Long Term Evolution
MAC	Media Access Control
MCS	Modulation and Coding Scheme
MS	Mobile Station
NACK	Not Acknowledgement
ODU	Outdoor Unit
OFDM	Orthogonal Frequency Division Multiplex
openWNS	open Wireless Network Simulator
PDU	Protocol Data Unit
PER	Packet Error Rate
PHY	Physical Layer
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
REC	Relay Enhanced Cell
RMS	Remote Mobile Station
RS	Relay Station
RSSI	Receive Signal Strength Indicator
SDU	Service Data Unit
SER	Symbol Error Rate
SINR	Signal-to-Interference+Noise-Ratio
SPID	Subpacket Identifier
SS	Subscriber Station
TCP	Transmission Control Protocol
TDD	Time Division Duplex
UE	User Equipment
UL	Up-link
VoIP	Voice over IP

1 INTRODUCTION

High cell capacities up to 1Gb/s are demanded by the International Telecommunication Union (ITU) for future IMT-Advanced systems. This requires the development of advanced techniques to increase the spectral efficiency of the whole system. Thereby, the focus for improvement may be on both - link level and system level. In this activity the focus is set on link level improvements. The different approaches investigated in this milestone are outlined in the following.

Dynamic adaptation of Automatic Repeat Request (ARQ) segment sizes depending on the current channel quality is investigated in Section 2.2. If the channel suffers from a high error rate Media Access Control (MAC) Service Data Units (SDUs) are segmented into small parts. Thus, if the transmission of one segment was erroneous, only few bits have to be retransmitted. On the other side, if the channel has a low error rate the SDUs are segmented in larger parts to reduce MAC signaling overhead.

The main goal of the joint optimization of ARQ and Forward Error Correction (FEC) tackled in Section 2.3 is to improve the service quality depending on the service type. If a service type, e.g. VoIP, requires low delays a strong FEC may be used to reduce the number of retransmissions. The resulting PDUs are large as much redundancy is added. In the rare case a transmission is erroneous, a Hybrid ARQ (HARQ) at the receiver may combine the erroneously received PDU and the retransmissions to increase the chance of correct decoding. For a service type that has no strict delay requirements, e.g. file transfer, the FEC may be weaker. By using the HARQ with a weak FEC the redundancy that is added to each PDU is small. Hence, the chance that a PDU is received erroneously is higher and more PDUs have to be retransmitted. The average delay of the PDUs is increased. However, as less redundancy is added to each PDU compared to delay critical service types the payload throughput is increased even if more retransmissions are necessary. The increased number of retransmissions is overcompensated by the reduced redundancy that is added to each PDU.

In Section 2.4, new mechanism on the acknowledgement of user's data by ARQ is proposed and evaluated. This mechanism is designed with the focus on the reduction of the MAC management overhead. The evaluation is performed for various setting of the ARQ parameters and PHY channel conditions. Moreover, scenarios with and without RSs are taken onto account in evaluation. The overhead of HARQ and its interaction with ARQ is also considered.

The flow control mechanism described in Section 3.1 increases the overall cell capacity of Relay Enhanced Cells (RECs). In RECs PDUs may get lost at Relay Stations (RSs) if the capacity of a connection from the RS to a Mobile Station (MS) is different from the capacity of the connection for that MS from the Base Station (BS) to the RS. A possible solution to avoid PDU loss is presented in the section. In Section 3.2 a mechanism for the efficient signalling of resource usage patterns is described.

2 LINK LEVEL RECONFIGURATION

2.1 Related Work

Generally, errors occur during data transmission in wireless networks. Erroneous packets cannot be used for further processing without a method of correction. For this purpose, wireless networks commonly use techniques based either on Automatic Repeat reQuest (ARQ) or Forward Error Correction (FEC) method. The ARQ mechanism uses a feedback channel for the confirmation of error-free packet delivery or for packet retransmission request. This method can increase a network throughput if radio channel conditions are getting worse (see section 2.3). On the other hand, the ARQ method increases the delay of packets by time spent for the retransmission of erroneous packets. The FEC method allows an increase in user's data throughput within an impaired channel quality by adding redundant coding information on the transmitter side. Both methods can be combined to Hybrid ARQ (HARQ).

All above mentioned methods should implement a mechanism at link layer that control and manage these techniques to achieve optimal performance on a wireless link. The ARQ in WiMAX networks is mandatory supported by all Base Stations (BS) as well as by all Mobile Stations (MS) according to [WiForum2009].

The performance of ARQ defined in [IEEE802.16e] depends on the setting of parameters such as size of user data carried in a frame, size of ARQ block, size of PDU (Packet Data Unit), value of retransmission timeout timer or on the type of packet acknowledgement [Lee2008]. Evaluation of the type of packet acknowledgment for different channel condition is presented in by [Kang2006] Kang and Jang. Tykhomyrov et. al. evaluate the ARQ performance for different ARQ parameters [Tykhomyrov2007]. This work is later on enhanced by analysis of the impact of PDU size on IEEE 802.16e networks performance while ARQ mechanism is used by Martikainen et. al. [Martikainen2008]. Sayenko et. al. provide a comparison of ARQ and HARQ performance in IEEE 802.16 networks [Sayenko2008]. This paper also compares the overhead size generated by ARQ and HARQ. The optimal PDU size and MAC (Medium Access Control) overhead due to the packets retransmission is analyzed by Hoymann [Hoymann2005]. Sengupta et. al. [Sengupta2005] propose to adjust the MAC PDU size depending on the channel state to achieve the best ARQ performance. The paper is extended for analysis of a combination of error correction techniques such as ARQ, FEC or MAC PDU aggregation on the VoIP speech quality [Sengupta2008]. Authors proof the improvement of VoIP speech quality by using these techniques. Chen and De Marca [Chen2008] investigate an optimization of ARQ parameter setting from the link throughput point of view. Kliazovich et. al. propose a cross-layer ARQ mechanism, which substitutes the transmission of TCP acknowledgment packet with a short request transmitted on the MAC layer of the wireless link [Kliazovich2008]. The cross-layer approach is investigated also in [Krishnamachari2003] by Krishnamachari et. al. The authors propose a novel adaptive cross-layer protection strategy for video transmission. Combination of application layer FEC and MAC layer ARQ and optimum setting of parameters of those techniques is also investigated in this paper.

Most of the above mentioned papers focus on the investigation of optimal ARQ parameters setting, but not too much research has been done on possible optimization of the ARQ procedure currently used at MAC layer. Therefore, the optimization of ARQ from the overhead reduction point of view while the packet delay is not negatively affected in comparison to conventional IEEE 802.16e ARQ is investigated. The proposed scheme is evaluated also for the scenario with enabled HARQ while mutual interaction between HARQ and ARQ entities [Maheshwari2008] is considered.

2.2 ARQ segment size

2.2.1 Goals

Goal of the dynamic Automatic Repeat Request (ARQ) segment size adaptation is to increase the individual link capacity between a Mobile Station (MS) and their serving Base Station (BS). Thereto, the segment size of Media Access Control (MAC) Service Data Units (SDUs) is adapted to the current channel quality. If the channel suffers from a high error rate the SDU is segmented into small parts. Thus, if the transmission of one segment was erroneous, only few bits have to be retransmitted. On the other side, if the channel has a low error rate the SDUs are segmented in larger parts to reduce the MAC signaling overhead.

2.2.2 Concept

The results of link-level simulations performed in the STRIKE project [IST-STRIKE] showed that OFDM symbol errors occur uncorrelated within a MAC frame. Under this assumption the Packet Error Rate (*PER*) calculates to:

$$PER = 1 - (1 - SER)^{N_{symbols}} \qquad \textbf{(1)}$$

where *SER* denotes the Symbol Error Rate (SER) and $N_{symbols}$ the number of OFDM symbols necessary to transmit the MAC Protocol Data Unit (PDU) containing the ARQ segment. The PER over SER is exemplary plotted in Figure 1 for different $N_{symbols}$ as set parameter. As can be seen in the figure, for a given SER the PER is the smaller the less OFDM symbols have to be transmitted per MAC PDU. Hence, to maximize the probability of correct reception of the ARQ segment, the segment size should be as small as possible. Additionally, if a small MAC PDU is transmitted erroneously only few OFDM symbols have to be retransmitted. But, a MAC header prepends each ARQ segment so that the segment can be delivered to the correct addressee, transmission errors can be recognized, e.g. through a Cyclic Redundancy Check (CRC) and the segment can be reassembled in the peer entity. The per ARQ segment overhead reduces the overall payload throughput of the link. Hence, for a low SER the ARQ segment size should be larger to maximize the payload throughput.

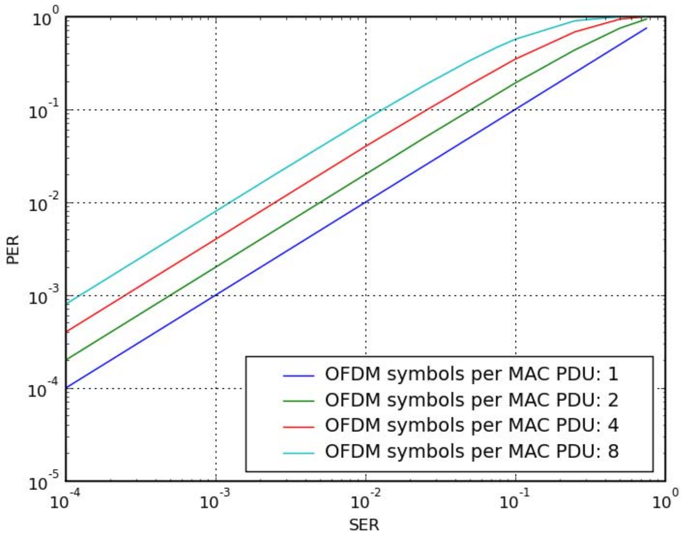


Figure 1: PER over SER for different MAC PDU sizes

The normalized payload throughput *PL* in dependency of *SER* calculates to:

$$PL = \frac{s}{h+s}(1 - SER)^{h+s} \qquad \textbf{(2)}$$

where *s* denotes the ARQ segment size in OFDM symbols, *h* the MAC header overhead in OFDM symbols and *SER* the symbol error rate. Here, *s* and *h* can be rational numbers. It is assumed that as long as the length of the MAC PDU (the sum of *h* and *s*) does not become too small Equation (2) still holds. Furthermore, acknowledgements are not modeled herein.

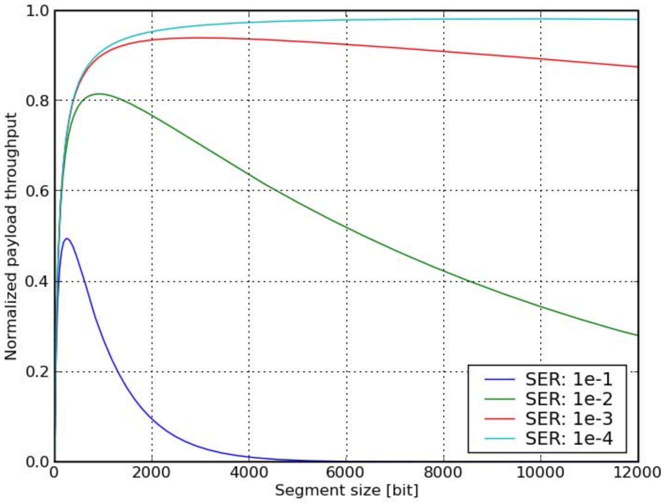


Figure 2: Normalized payload throughput for different SER levels (symbol size: 96bit)

In Figure 2 the normalized payload throughput over the segment size is plotted with the SER as set parameter. As can be seen, for smaller SER levels the optimal ARQ segment size increases. Thus, there has to be an optimal ARQ segment size that depends on the current SER to maximize the payload throughput. Considering Equation (2) the optimal ARQ segment size calculates to:

$$s_{opt} = \sqrt{\frac{h^2}{4} - \frac{h}{\ln(1-SER)}} - \frac{h}{2} \qquad \textbf{(3)}$$

where s_{opt} denotes the optimal segment size in number of OFDM symbols, h the MAC header size in OFDM symbols and SER the symbol error rate. The optimal ARQ segment size in dependency of the SER is plotted in Figure 3 with the MAC header size as set parameter.

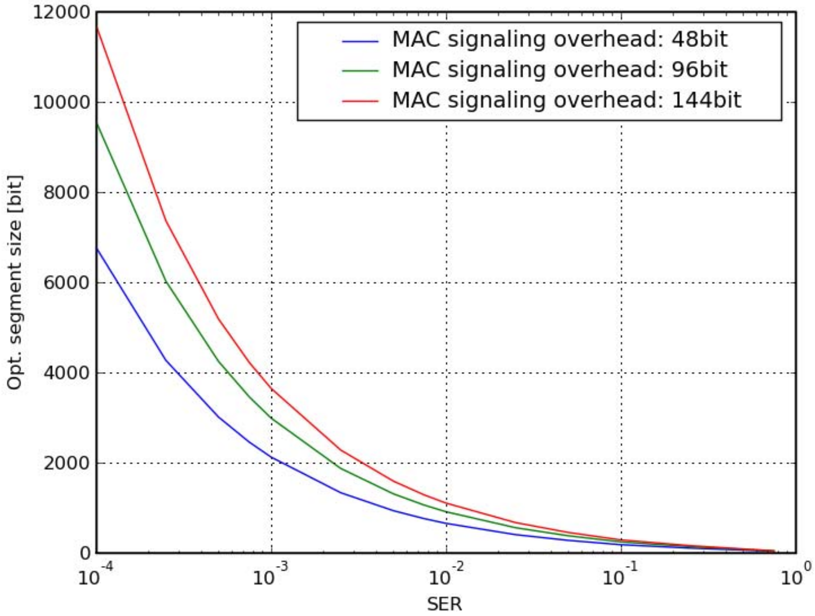


Figure 3: Optimal segment size over SER (symbol size: 96bit)

2.2.3 Analytical results

Based on link level mappings derived by simulations within the STRIKE project the payload throughput over the Signal-to-Interference+Noise-Ratio (SINR) can be calculated for a given PDU size. The according equation is derived in several steps:

$$P_{errorfree,\,MCS} = \left(1 - f_{MCS}(SINR)\right)^{s+h} \qquad \textbf{(4)}$$

$P_{errorfree,MCS}$ is the probability that a PDU has been received error free, $f_{MCS}(x)$ is the link level mapping function that maps the *SINR* to an SER for a given Modulation and Coding Scheme (MCS), s is the ARQ segment size in OFDM symbols and h is the MAC header size in OFDM symbols.

$$T_{MCS} = P_{errorfree,\,MCS} \frac{N_{bps,MCS} * N_{spf}}{l_{frame} * \left(1 + N_{pre,\,cyclic}\right)} \qquad \textbf{(5)}$$

T_{MCS} is the overall data throughput, $N_{bps,MCS}$ is the number of uncoded bits transmitted per OFDM symbol for a given MCS, N_{spf} is the number of OFDM symbols per frame, l_{frame} is the length of a frame in seconds and $N_{pre,cyclic}$ is the length of the cyclic prefix in OFDM symbols, e.g. ¼.

$$PL_{MCS} = \frac{s}{s+h} T_{MCS} \qquad \textbf{(6)}$$

PL_{MCS} determines the payload throughput based on the segment size s and the MAC overhead h for a given throughput value T_{MCS}. All system parameters used for the following analytical evaluation are listed in Table 1. According to [IEEE802.16e] the header size h calculates to 96bit, see Figure 4.

Table 1: System parameters for analytical evaluation

System parameter	Value
$N_{bps,MCS}$	BPSK1/2: 96bit QPSK1/2: 192bit QPSK3/4: 288bit 16QAM1/2: 384bit 16QAM3/4: 576bit 64QAM1/2: 768bit 64QAM3/4: 864bit
N_{spf}	720
l_{frame}	10ms
h	96bit
$N_{pre,cyclic}$	1/4

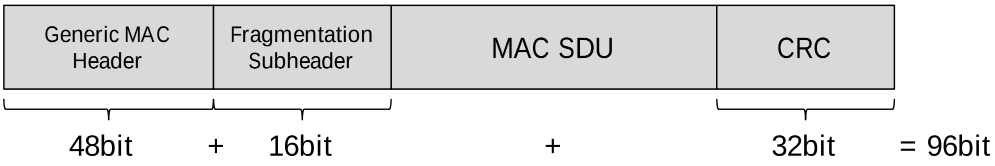


Figure 4: Calculation of ARQ segment header size

The resulting graphs for the different MCSs are shown in Figure 5, Figure 6 and Figure 7 for the segment sizes 1000bit, 2038bit and 12000bit. As can be seen, for small ARQ segment sizes each MCS can already be used at lower SINR levels compared to the larger ARQ segment sizes, e.g. for a segment size of 1000bit already at 14dB SINR QAM16 3/4 may be used whereas for a segment size of 12000bit an SINR of at least 15dB is necessary. On the other hand, the maximum payload throughput is smaller for smaller ARQ segment sizes, e.g. the maximum throughput for QAM16 3/4 is about 38Mb/s, whereas for a segment size of 12000bit the max payload throughput is about 41Mb/s.

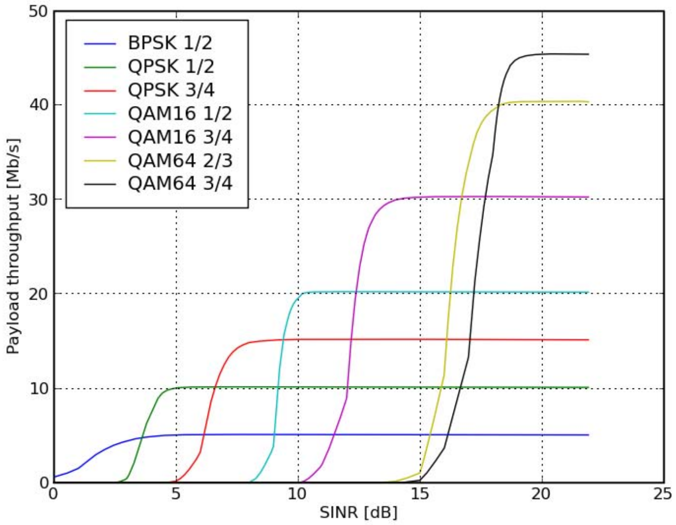


Figure 5: Payload throughput over SINR for segment size of 1000bit

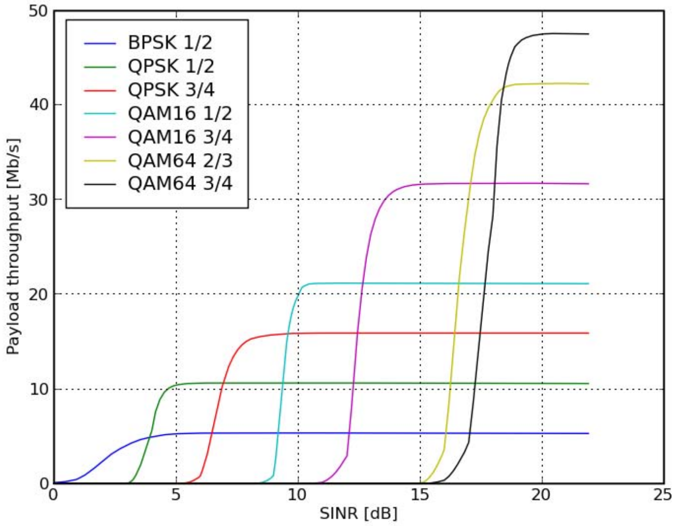


Figure 6: Payload throughput over SINR for segment size of 2038bit

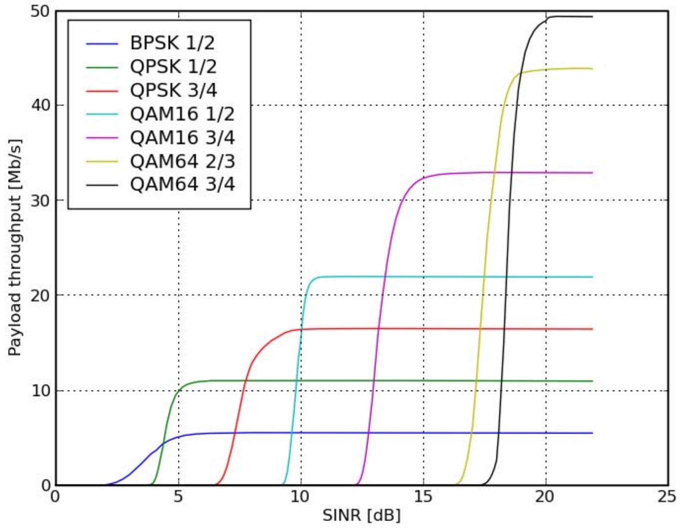


Figure 7: Payload throughput over SINR for segment size of 12000bit

By substituting *SER* through $f_{MCS}(SINR)$ in Equation (4) the optimal segment size depending on the SINR level can be calculated for the different MCSs. The results are shown in Figure 8. The segment size is clipped at 12000bit as larger sizes usually do not occur in real world networks.

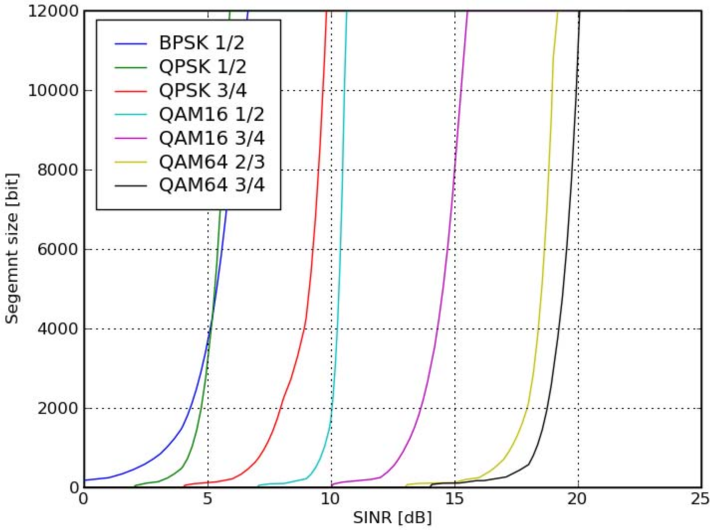


Figure 8: Optimal segment size over SINR

If furthermore in Equation (4) and Equation (6) s is substituted by s_{opt} as calculated in Equation (3), the payload throughput for MAC PDUs containing optimally segmented ARQ segments can be plotted, see Figure 9. As expected, the dynamically adapted segmentation combines the advantages of small segment sizes for low SINR levels, e.g. for 11dB transmissions with QAM16 ¾ are already feasible, whereas the MAC overhead for SINR levels over 16dB is kept small for QAM16 ¾ so that the same throughput as for a fix segment size of 12000bit is reached.

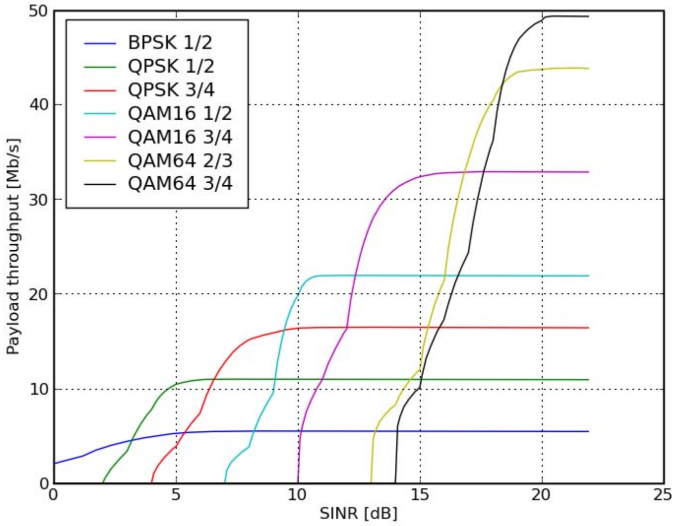


Figure 9: Payload throughput for optimally segmented MAC SDUs

Usually, only the maximum throughput envelope of a link level mapping is important as switching between the different MCSs according to this envelope maximizes the link and hence also the cell capacity. In Figure 10 the maximum throughput envelopes for dynamic segmentation and for different fix segment sizes are plotted. Thereby, the graph for the optimally segmented ARQ segments represents the upper bound limit of the payload throughput. All graphs for fixed segment sizes are always below this graph or match it. For small segment sizes, e.g. 1000bit (green graph), the graph matches well the graph for optimal segmentation near the switching points between different MCSs up to 1dB above the switching point. Then, the payload throughput diverges considerably from the optimal value. Unlike, for large fix segment sizes, e.g. 12000bit (red graph), the graph diverges much from the optimal graph near the switching point up to 1dB above but matches it well for larger SINR levels. The red curve (segment size: 2038bit) shows a trade-off between both extreme cases and does not diverge so much from the optimal graph as both other graphs but also does not match the optimal graph for so much SINR levels.

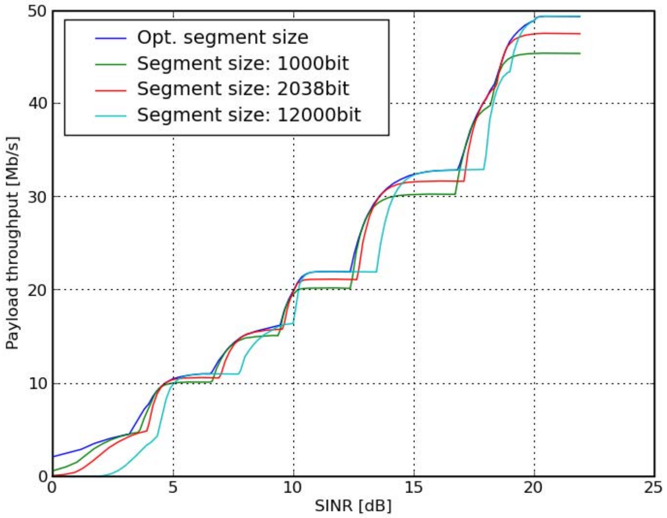


Figure 10: Maximum throughput envelopes for dynamic and fix segment sizes

In Figure 11 the differences in payload throughput for fix segment sizes compared to the optimal segment size are plotted over the SINR level. As can be seen, for small segment sizes (blue graph) relative maximums in the difference are at that SINR levels where for large segment sizes (red graph) relative minimums are and vice versa. Again, a medium segment size (green graph) shows the trade-off between both extreme cases.

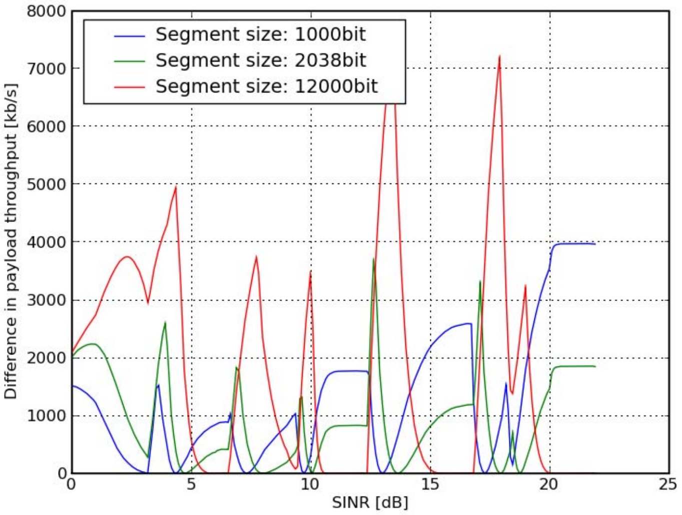


Figure 11: Difference in payload throughput for fix segment sizes compared to optimal segment size

Assuming an interference free single-cell scenario with an omni-directional transmitting BS, free space propagation and uniformly distributed positions of all MSs, the mean cell capacity for the optimal as well as for fixed segment sizes can be calculated. Thereto, the payload throughputs at the different SINR levels are weighted according to the probability that a MS receives transmissions at that SINR level. Then, the weighted values are summed up. The result is the mean cell capacity. According to [Hoymann2008] it is reasonable to define the cell border through a minimum required SINR level of 6dB. Hence, only the SINR levels between 6dB and 22dB are weighted and summed up in this case. The weight factors are shown in Figure 12, the results in Table 2.

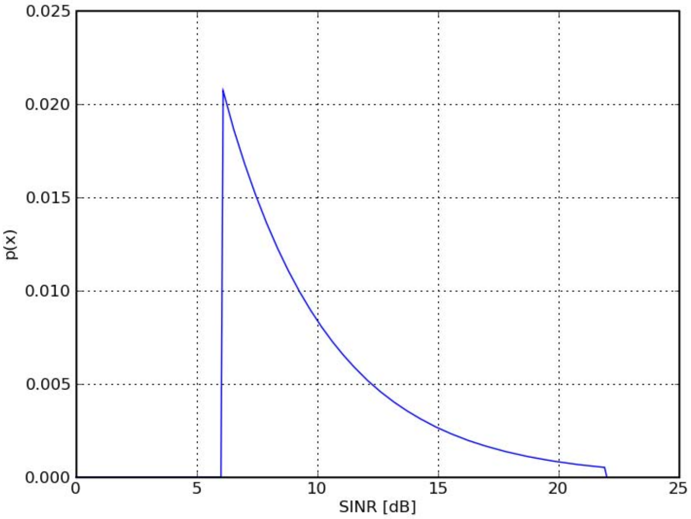


Figure 12: PDF of the SINR distribution in a single cell scenario with free space propagation and uniformly distributed MSs

Table 2: Cell capacities for different segment sizes

Segmentation	Cell capacity
1000bit (fix)	18.2Mb/s
2038bit (fix)	18.4Mb/s
12000bit (fix)	17.7Mb/s
Dynamic	19.1Mb/s

The maximum cell capacity for optimal dynamic segmentation is about 19.1Mb/s. For an optimally chosen fix segment size of 2038bit the mean cell capacity is about 18.4 Mb/s. This is only about 3.25% less than for dynamic segmentation. Even for very small and large fix segment sizes the cell capacity loss is small (4.56% at 1000bit, 7.10% at 12000bit).

2.2.4 Conclusions

The marginal gain that can be reached does not justify the use of dynamic segmentation as it introduces additional complexity for signaling segment sizes and processing PDUs in the MAC layer.

2.3 ARQ throughput measurement

An impact of enabling and disabling of the ARQ on the network throughput is measured on the real 802.16-2004 WiMAX equipment. The throughput measurements are done for various RSSI and various modulation schemes in downlink. The equipment made by Alvarion [Alvarion2007] (more details are presented below) is used. Software Ipfer [NetLab2005] is considered for throughput measurement and for data flow generation. The measurement of each configuration (RSSI and modulation scheme) is an average of 60 s duration of a measurement. This means, each point in figures present an average bit rate per 60s for given modulation and RSSI.
The parameters used for measurement are presented in Table 3. From the supported list of modulation, 64QAM, 16QAM, QPSK and BPSK with ¾ code ratio are selected. The BS uses QoS profile corresponding to BE (Best Effort) service. Also the Adaptive Modulation functionality is disabled.

Table 3: Parameters for throughput measurement

Parameter	**Value**
Modulation	64QAM, 16QAM, QPSK, BPSK
FEC Code Ratio	¾
Type of Service	Best Effort
Adaptive Modulation	Disabled
Frequency Band	3.5GHz
Channel bandwidth	3.5 MHz
RSSI	From -93 dBm to -68 dBm

The measurement is performed using attenuator elements (with attenuation A_c) instead of outdoor measurement since the WiMAX equipment works in 3.5 GHz licensed frequency band. The RSSI is calculated based on the following formula:

$$RSSI = L_T - A_c [\text{dBm}] \quad \textbf{(7)}$$

where L_T presents transmission level at BS.

The connection diagram used for measurement is shown in Figure 13. The Alvarion BreezeMAX 3500 mBST base station and Alvarion BreezeMAX-BST-AU-ODU-3.5a OutdoorUnit (ODU) is deployed at the transmitting side. At the receiving side is employed Alvarion BreezeMAX-CPE-ODU-PRO-SE-3.5a unit representing the SS.

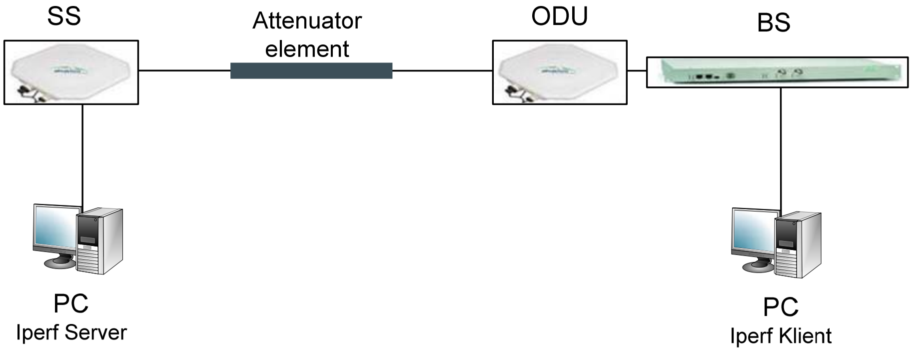


Figure 13: Connection diagram for measurement

The parameters of implemented equipments are depicted in Table 4.

Table 4: Equipment parameters

Base Station Alvarion BreezeMAX 3500 mBST	
Parameter	**Value**
Adaptive Modulation	Disabled
Frequency Band	3.5GHz
Channel bandwidth	3.5 MHz
Outdoor Unit Alvarion BreezeMAX-BST-AU-ODU-3.5a	
Frequency band	3429.25 MHz (UL), 3529.25 (DL)
Duplex	FDD
Transmit power	13-28 dBm
Subscriber Station Alvarion BreezeMAX-CPE-ODU-PRO-SE-3.5a	
Frequency band	3429.25 MHz (UL), 3529.25 (DL)
Duplex	FDD
Channel bandwidth	3.5 MHz

The results of measurements are presented in Figure 14 and Figure 14. The results show the considerable impact of ARQ on the throughput when the radio channel conditions become worse. The most significant impact can be observed in the advanced modulations such as 64QAM or 16 QAM. On the other hand, the ARQ brings an increase of overhead which results in lower data throughput while the channel conditions are good. This is noticeable especially for BPSK (approximately 10% decrease). By using of more sophisticated modulations (QPSK, QAM), the decrease of throughput is negligible relatively to the absolute values. However, the absolute level of overhead produced by ARQ is similar for all modulations.

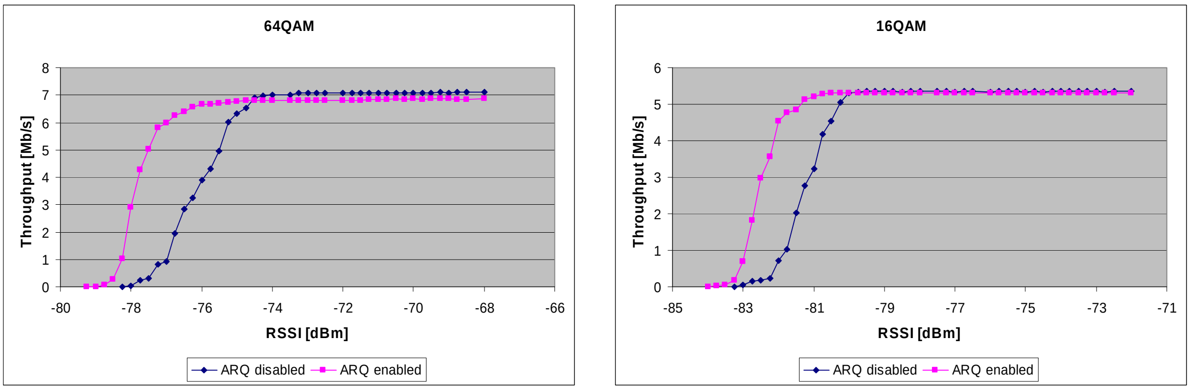


Figure 14: Throughput measurement for modulation 64QAM and 16QAM

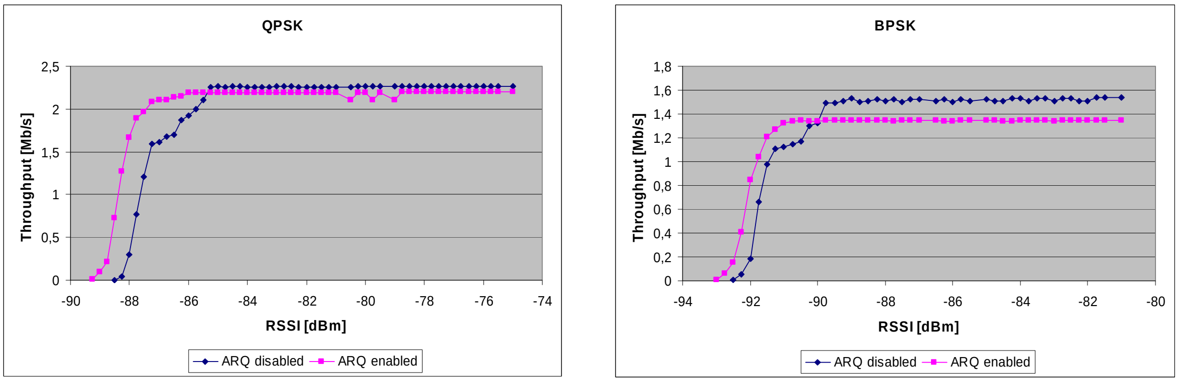


Figure 15: Throughput measurement for modulation QPSK and BPSK

2.4 MAC management overhead of ARQ

The ARQ assumes a segmentation of user data into blocks and their transmission to the receiver. The receiver checks obtained data for errors and replies to the transmitter with request on retransmission of erroneous blocks. The channel quality can be expressed by a parameter representing the ratio between blocks received with errors and all transmitted blocks − Block Error Rate (BLER). The conventional IEEE 802.16e ARQ and the proposed methods are described in the following subsections.

2.4.1 Conventional ARQ according to IEEE 802.16e

Each burst from a user carried in a frame is segmented into PDUs. A PDU consists several blocks N_{block}. The number of blocks is given by following equation:

$$N_{blocks} = \frac{S_{data}}{S_{ARQ\_block}} \tag{8}$$

where S_{data} is a total size of data in one frame by one user, parameter S_{ARQ_block} represents a block size defined by parameter denoted in the standard as ARQ_Block_Size [IEEE802.16e]. This parameter is carried in TLV (Type/Length/Value) section of registration messages (REG-REQ/RSP) exchanged between BS and MS (see [IEEE802.16e]). The parameter ARQ_Block_Size can take values from the following range: 16, 32, 64, 128, 256, 512 and 1024 bytes. A sequence of consecutive blocks is transmitted in the MAC PDU. The receiver checks the received data and sends an acknowledgment (ACK) feedback message to the transmitter. The feedback is sent in the subsequent frame after the data transmission. The feedback message contains 8 bit field Message ID and field ARQ_Feedback_Payload. The ARQ payload can be carried either via standalone ARQ feedback message or by piggybacking the ARQ payload to the user's data block. The payload is always carried in a single PDU. The ARQ_Feedback_Payload contains one or more ARQ_Feedback_IE (see Table 5) where IE stands for Information Element.

Table 5: Structure of ARQ_Feedback_IE [IEEE802.16e]

Syntax	Size	Notes
CID	16 bits	Connection ID
Last	1 bit	Identify the last IE in ARQ_Feedback
ACK Type	2 bits	0x0...Selective ACK 0x1...Cumulative ACK 0x2...Cumulative with Selective 0x3...Cumulative with Block Sequence
BSN	11 bits	Block Sequence Number (0...2047)
Number of ACK Map	2 bits	Number of Maps (M) = 1,2,3 or 4
Maps	M x 16 bits	Selective (16 blocks) or Cumulative maps (2 x 64 blocks / 3 x 16 blocks) Cumulative maps: 1 bit sequence format (2 or 3 blocks), 2/3bits Sequence ACK (ACK/NACK of sequence), (2x6) / (3x4) bits Sequence length

The size of an IE of each ARQ feedback message can be calculated according to equation:

$$Size_{ARQ\_FB\_IE} = 32 + (M \times 16) \tag{9}$$

where M represents a number of maps carried in one ARQ_Feedback_IE (see Table 5). The overall size of whole feedback message is given in Equation (9).

$$Size_{ARQ\_FB} = 8 + \sum^{N_{IE}} Size_{ARQ\_FB\_IE_{N_{IE}}} \tag{10}$$

where N_{IE} is a number of information elements carried in one ARQ Feedback message and the number *8* (bits) represents the ARQ feedback message overhead (Message ID field). The overhead transmitted in all considered frames (N_{frame}) is equal to the sum of partial overheads over the N_{frame} :

$$OH_{ConvARQ} = \sum^{N_{frame}} Size_{ARQ\_FB_{Nframe}} \tag{11}$$

The principle of conventional ARQ method according to the IEEE 802.16e standard and the structure of user's information carried in the frame are depicted in Figure 16.

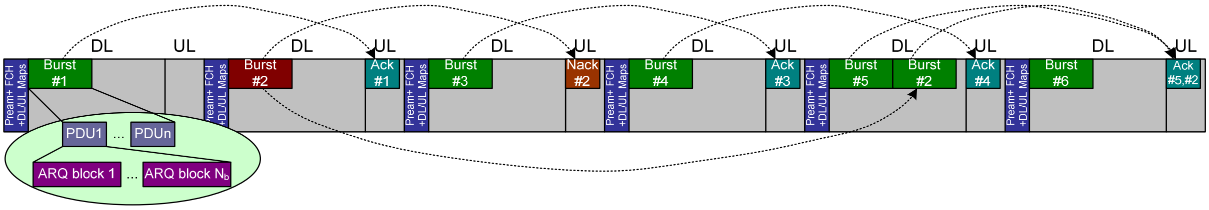


Figure 16: Principle of conventional ARQ

All transmitted blocks have to be confirmed by ACK or by negative ACK (NACK) even if all blocks are received without errors. Therefore, the size of overhead per frame and per user depends especially on the number of blocks transmitted in one frame by one user. The IEEE 802.16e standard defines four types of acknowledgments: Selective ACK entry, Cumulative ACK entry, Cumulative with Selective ACK entry and Cumulative with Block Sequence ACK entry. The first type of acknowledgment uses selective maps to provide feedback to the transmitter. Each bit set to "1" in the selective map indicates error-free receiving of the corresponding ARQ block. The BSN corresponds to the most significant bit in the map. The second type, Cumulative ACK entry, is based on the utilization of sequence maps. A sequence map defines a group of consecutive blocks where each group includes a sequence of only erroneous blocks or sequence of only error free blocks. The sequence maps can contain two or three sequences with a length of 64 or 16 blocks respectively. The third type of ACK combines the previous two types. Finally, the last type combines the second type with ability to acknowledge ARQ blocks in the form of block sequences.

The retransmission of erroneous blocks cannot be provided sooner than in the third block after the first transmission since the transmitter receives NACK in the following frame after transmission (2nd frame). Hence a request for additional resources can be created earliest at the next frame (3rd frame). Therefore, the dedicated resources are not available before the 4th frame. The retransmitted data (burst #2 in Figure 16) can be transported either together with normally ordered data (burst #5 in Figure 16) or the fresh data (burst #5 in Figure 16) can be delayed by one frame. It causes a delay of retransmitted packets with duration that corresponds to at least 3 times frame duration (e.g. if the frame duration is 10 ms, the packet delay is at least 30 ms).

Fresh data and retransmitted data are sent in one frame only if the requested capacity (fresh data + retransmitted data) is available. The WiMAX technology implements Stop-and-Wait mechanism that requests a confirmation of the previous block before transmitting subsequent blocks. The number of blocks that can be unconfirmed before transmission of the consequent blocks is defined in the standard by parameter ARQ_Window_Size.

2.4.2 Proposed ARQ schemes

A number of blocks received with errors increases as decreases the link quality between transmitter and receiver. Thus, if the BLER increases, the amount of NACK blocks also increases. We can assume that the major part of links with enabled ARQ have enough quality to transfer most of blocks without errors (confirmed by ACK) while the number of blocks with errors (confirmed by NACK) is kept to minimum. In such case, the transmission of ACK blocks appears more often than NACK blocks. If we consider that only NACK blocks are sent, the ARQ overhead can be significantly reduced. The above mentioned assumption is a basis for all following proposals.

2.4.2.1 ARQ Scheme I – Only Negative ACK

The first proposed scheme assumes ARQ feedback message and ARQ_Feedback_IEs with the same structure as the conventional IEEE 802.16 ARQ feedback message. However in this proposal, the ARQ feedback is only sent if a received PDU contains at least one erroneous block. If all blocks in the PDU are error free, no feedback is sent (see Figure 17). The PDU is assumed to be correctly transferred if the transmitter receives no feedback in the following W frames after the transmission (W=1 in Figure 17). To define W, a new ARQ parameter, called as ACK_Window, is introduced. If the block is received with errors, the ARQ feedback message is transmitted in the same way and with the same content as in the conventional ARQ. An error-free block is acknowledged after W frames at the latest. It means that if no NACK is received in the one of the following W frames, the block is supposed to be correctly received, i.e. as it would be confirmed by ACK. Therefore, the request for the retransmission of blocks with at least one error should be sent within one of the subsequent W frames. If the feedback with NACK is lost, the data belonging to the delay sensitive services (e.g. VoIP) are assumed to be lost since the delay caused by repeated ARQ retransmission is very significant. In case of services not sensitive to delay, data belonging to lost NACK can be retransmitted using upper layer protocols, e.g., TCP (Transmission Control Protocol). As the probability of lost packet or packet with errors together with the NACK feedback is very low, the increase of overhead due to upper layer protocols is negligible.

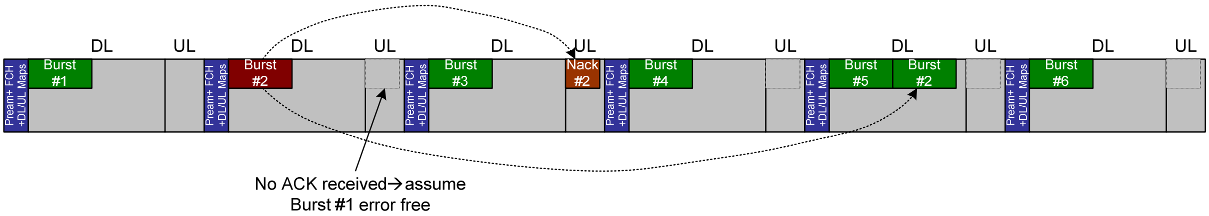


Figure 17: Principle of proposed ARQ scheme I

This proposed scheme does not need any modifications of ARQ MAC management messages, besides specification of the ACK_Window parameter. The description of the parameter is shown in Table 6. This parameter is carried in the registration messages (REG-REQ/RSP) and in messages related to the dynamic service management (DSx-REQ/RSP) [IEEE802.16e]. These messages are only transmitted during a registration of a MS to the network and during change of dynamic services. Therefore, the increase of overhead is insignificant in comparison with the overhead generated by ARQ acknowledgements.

Table 6: Definition of the parameter ACK_Window

Length	Value	Description
1 byte	0...64	The number of frames after which the belonging block is considered as an error free (as it could be confirmed by ACK).

The size of ACK feedback message can be calculated according to (Equation (10)). The overhead saving is achieved since not all transmissions have to be acknowledged by ARQ feedback message. The overall overhead of proposed ARQ scheme I is a sum of ARQ overhead created in each frame over number of frames. It can be calculated according to the next equation:

$$OH_{SchemeI} = \sum^{N_{frame}} Size_{ARQ\_FB_{Nframe}} \tag{12}$$

2.4.2.2 ARQ Scheme II – BSN of blocks with errors

The second proposed scheme is based on the same assumptions as the first one. The ACK feedback is likewise transmitted only if there is at least one erroneous block. A block is assumed to be error-free if no feedback is received in one of the following W frames after the transmission of appropriate data frame. Both proposals differ among each other in the structure of retransmission request. The ARQ scheme II slightly modifies the structure of ARQ_Feedback_IE. The conventional ARQ feedback message carries a set of ACK maps (see Table 5). Instead of these maps, the ARQ scheme II carries the set of BSNs related to erroneous blocks. Therefore, the ARQ feedback message contains only one IE field and the fields “Last” and “ACK Type” can be omitted. The format of modified ARQ feedback message is shown in Table 7.

Table 7: Structure of modified ARQ_Feedback_IE according to ARQ scheme II

Syntax	Size	Notes
CID	16 bits	Connection ID
Number of BSNs	10 bits	Number of BSNs (B) = 1...1024
Set of BSN	B x 11 bits	Set of Block Sequence Numbers (0...2047)
reserve	0-8	Align a message length to bytes

The maximum number of BSNs can be 1024 since ARQ_Window_Size is a half of the range of BSN (2^{11}=2048) [IEEE802.16e]. In case of the ARQ scheme II, the size of ARQ feedback message is given by equitation:

$$Size_{ARQ\_FB\_II} = 8 + 26 + (B \times 11) + res \tag{13}$$

where *B* is the number of BSNs included in a message and *res* is the number of bits used for an alignment of the message length to bytes. Only one IE filed is always carried in an ARQ feedback message since IE can carry BSNs of all erroneous blocks.

The total overhead due to ARQ scheme II is a sum over the overhead in all frames within the transmission:

$$OH_{SchemeII} = \sum^{N_{frame}} Size_{ARQ\_FB\_II\,N_{frame}} \tag{14}$$

The ARQ scheme II reduces the overhead especially for low values of BLER. For high value of BLER can be assumed an opposite idea – transmit only confirmation of error free packets (ACK). It will be profitable only for very high level of BLER (over approx. 80%) and it is almost impossible to reach this state in the real networks since the network would be overloaded by retransmitted packets.

2.4.2.3 ARQ Scheme III – Combination of ARQ Scheme I & II

The last proposed scheme, ARQ scheme III, is a combination of the previous two. This scheme dynamically selects the best one from the ARQ scheme I, ARQ scheme II and conventional IEEE 802.16e ARQ.

The ARQ scheme III introduces a new field (denoted ARQ Scheme) in ARQ_Feedback_IE that is used to decide which of the schemes should be applied in given moment. The selection of the scheme is based on the per frame calculation of minimum overhead generated in each frame. The modified structure of ARQ_Feedback_IE message is presented in Table 8.

Table 8: Structure of ARQ_Feedback_IE according to ARQ scheme III

Syntax	Size	Notes
CID	16 bits	Connection ID
ARQ Scheme	2 bits	0x0…Conventional ARQ (802.16e) 0x1…ARQ Scheme I 0x2…ARQ Scheme II 0x3…Reserve
if ARQ Scheme =0x0 or 0x1 {		
Last	1 bit	Identify the last IE in ARQ_Feedback
ACK Type	2 bits	0x0...Selective ACK 0x1...Cumulative ACK 0x2...Cumulative with Selective 0x3...Cumulative with Block Sequence
BSN	11 bits	Block Sequence Number (0...2047)
Number of ACK Map	2 bits	Number of Maps (M) = 1,2,3 or4
Maps	M x 16 bits	Selective (16 blocks) or Cumulative maps (2 x 64 blocks / 3 x 16 blocks) Cumulative maps: 1 bit sequence format (2 or 3 blocks), 2/3bits Sequence ACK(ACK/NACK of sequence), (2x6) / (3x4) bits Sequence length
}		
if ARQ Scheme =0x2 {		
Number of BSNs	10 bits	Number of BSNs (B) = 1...1024
Set of BSN	B x 11 bits	Set of Block Sequence Numbers (0...2047)
}		
reserve	0-8	Align a message length to bytes

With regards to the above mentioned structure of ARQ_Feedback_IE, the overhead generated by ARQ scheme III by a user in one frame can be calculated according to the following equation:

$$Size_{ARQ\_FB\_III} = 8+18+\min\left\{\sum^{N_{IE}} 16+16\times M_{N_{IE}}, 10+B\times 11\right\}+res \qquad \textbf{(15)}$$

where N_{IE} is the number of IEs carried in one ARQ feedback message, M_{NIE} corresponds to the number of ACK maps in ARQ_Feedback_IE, B is the number of BSNs included in one message and *res* is the number of bits used for an alignment of the feedback message length to bytes. The overhead generated by ARQ scheme III is given by the following equitation:

$$OH_{SchemeIII} = \sum^{N_{frame}} Size_{ARQ\_FB\_III_{N_{frame}}} \qquad \textbf{(16)}$$

2.4.3 Impact of proposed schemes on overhead for scenario without RS

The simulator, developed in MATLAB, focuses on the evaluation of overhead generated by ARQ procedure in the uplink direction by one user (see Figure 18).

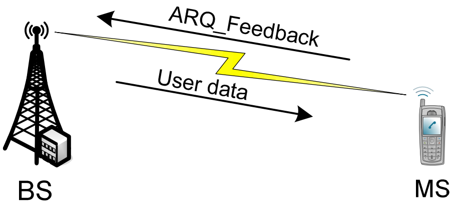


Figure 18: Link level simulation scenario

At the beginning of the simulation, all simulation and link parameters are set up according to values mentioned in Table 9.

Table 9: Simulation parameters for scenario without RSs

Parameter	Value
Number of frames	5 000
BLER [%]	0 – 20
ARQ_Block_Size [bytes]	16 – 1024
PDU size [blocks]	1 – 32
ACK Types	Selective, Cumulative
Size of data in each DL frame [bytes]	1024, 4096

The number of frames represents an amount of frames transmitted from the BS to the MS. The overhead size is evaluated per all transmitted frames. A frame consists of one or several PDUs and a PDU itself contain one or several ARQ blocks. The frames are subsequently sent by the BS to MS. A vector indicating positions of blocks with/without errors is created for each frame based on the given value of BLER. The MS responds to BS by sending an ARQ feedback message that includes selected ARQ scheme, ACK Type and a vector of errors in the transmission. According to the feedback message, the BS retransmits erroneous blocks as soon as possible, but not sooner than the third frame after the original transmission. The size of user’s data in a DL frame is kept the same within the simulation run (1024 bytes or 4096 bytes).

This procedure is repeated until all frames are sent to the MS and the MS confirms error-free reception of all blocks. The same vectors indicating positions of blocks with/without errors are considered in all ARQ schemes.

2.4.3.1 Results

The obtained simulation results are presented in Figure 19 – Figure 22. All figures describe dependence of the ARQ overhead on BLER. The *y* axis in figures indicates a recalculation of absolute values of the overhead into the relative values. As the reference value is taken the overhead of the conventional ARQ with selective ACK and BLER= 0%. The total absolute overhead is highlighted in figures with bolt font. The total absolute overhead at BLER=0% only depends on the number of blocks per a frame; just this value influents number of ACK maps carried in the ARQ feedback message of the conventional ARQ. The reference value is 508 kB for ARQ_Block_Size=16 B and for the user data size equal to 1024 B. The corresponding referential value is approximately 273 kB while ARQ_Block_Size is equal or higher than 64 B and the size of user data is equal to 1024 B. This value is independent on other parameters since the number of blocks per frame is always equal or less than 16. All ACKs/NACKs can be carried in one selective ACK map. The overhead of conventional ARQ varies according to BLER since the length of maps depends on the number of blocks in a belonging frame. The amount of blocks in a frame differs due to the retransmission of erroneous blocks.

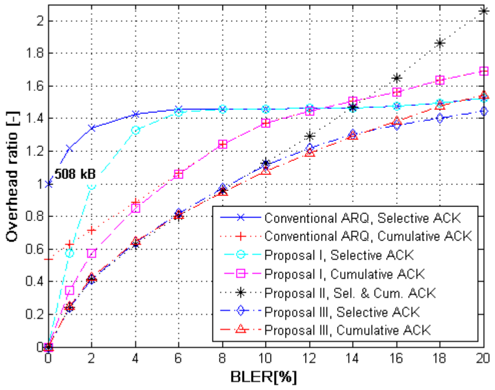


Figure 19: ARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 1 block and Size of user data = 1024 B/ frame

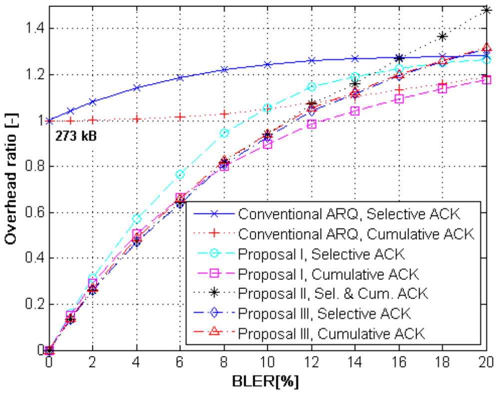


Figure 20: ARQ Overhead vs. BLER for ARQ_Block_Size = 64 B, PDU Size = 1 block and Size of user data = 1024 B/ frame

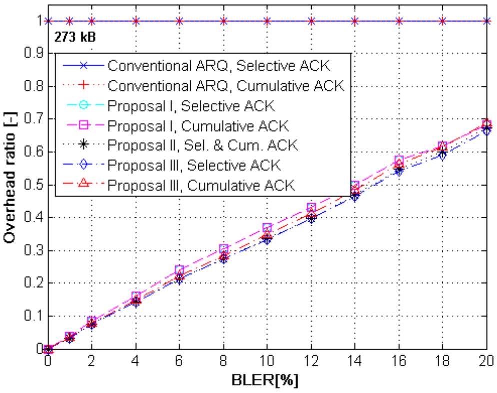


Figure 21: ARQ Overhead vs. BLER for ARQ_Block_Size = 256 B, PDU Size = 1 block and Size of user data = 1024 B/ frame

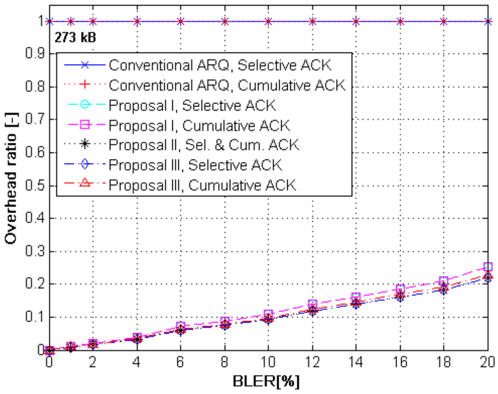


Figure 22: ARQ Overhead vs. BLER for ARQ_Block_Size = 1024 B, PDU Size = 1 block and Size of user data = 1024 B/ frame

Figure 19 – Figure 22 show an impact of the BLER on the size of ARQ overhead for different values of ARQ_Block_Size. Each figure compares the conventional ARQ using selective and cumulative ACK (solid line with cross mark and dotted line with plus mark respectively, both lines overlaps in Figure 21and Figure 22) with three versions of ARQ proposals. As it could be assumed the cumulative ACK shows better performance for low BLER since the low BLER leads to the longer consecutive sequences of blocks without errors. Hence less ACK maps is required to confirm all blocks by cumulative maps in comparison with selective maps. The difference between selective and cumulative ACK becomes negligible as the value of ARQ_Block_Size increasing (compare the same lines among Figure 19 – Figure 22).

The decrease of ARQ overhead using ARQ scheme I (dash line with circle or square marker) can be observed from all figures. The size of ARQ overhead decreases significantly for low values of BLER. The overhead of conventional and proposed scheme I converge. The ARQ overhead saving is more significant as simultaneously BLER and ARQ_Block_Size values become higher since the bigger block size leads to the lower number of blocks in a PDU. Therefore the number of retransmitted blocks is also decreased due to the lower number of block contained in one PDU (all blocks belonging to one PDU are retransmitted if there is at least one erroneous block). In case of ARQ scheme II (dotted line with asterisk marker), the overhead reduction is more significant for lower BLER in comparison with the ARQ scheme I. As BLER grows, the ARQ scheme II produces higher ARQ overhead than the conventional ARQ or ARQ scheme I. The impact is more significant when using high values of ARQ_BLOCK_Size. The ARQ scheme III (dash line with diamond or triangle marker) gives the best results since it selects the best ARQ scheme (from the overhead minimization point of view) for each block. In exceptional case, the overhead created by proposal III can be higher than overhead of the other proposals due to 2-bits field *ARQ_Scheme* in IE (see Table 8).

From Figure 19 – Figure 22 can be observed reduction of absolute overhead for all proposed ARQ schemes as the value of ARQ_Block_Size increasing. Additionally, the efficiency of the overhead reduction of all proposed ARQ schemes become more similar as the ARQ_Block_Size increasing.

The assumption of only 1 block per PDU was considered in all previous figures. The impact of the different number of blocks per PDU on the overhead is shown in Figure 23 – Figure 26 (ARQ_Block_Size = 16 bytes in all figures). The results indicate a very significant overhead increase as the PDU Size and BLER grow. This increase is significant especially in case of ARQ scheme II. This is due to the retransmission behaviour when an erroneous block results in retransmission of all blocks included in the same PDU. Therefore the ARQ scheme II is more suitable for low values of BLER and low number of blocks per PDU. The ratio of total ARQ overhead among conventional ARQ and the proposed schemes significantly depends on the value of BLER. When comparing the selective and cumulative ACK, the cumulative ACK is more suitable for very low values of BLER, with regards to PDU Size. In case of ARQ scheme III, the overhead is reduced in the whole simulated BLER range.

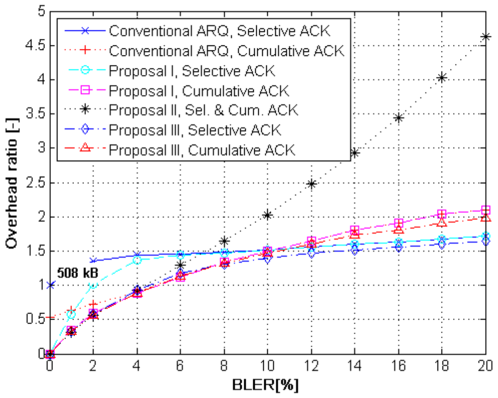


Figure 23: ARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 2 blocks and Size of user data = 1024 B/ frame

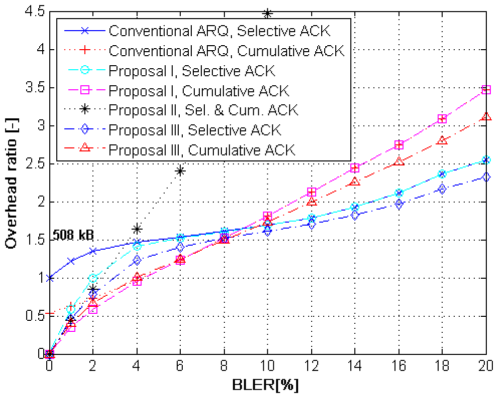


Figure 24: ARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 4 blocks and Size of user data = 1024 B/ frame

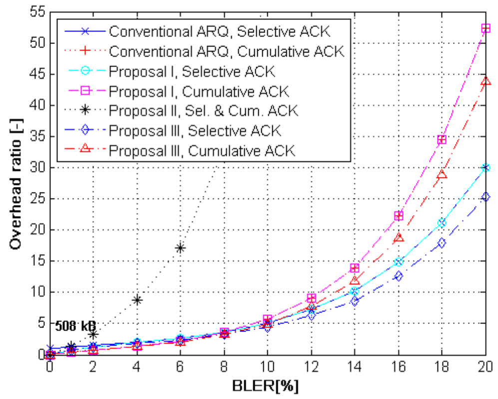


Figure 25: ARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 16 blocks and Size of user data = 1024 B/ frame

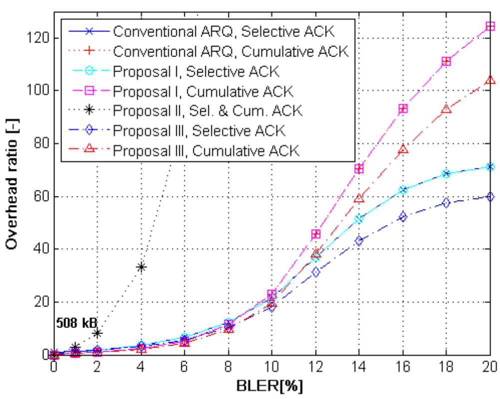


Figure 26: ARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 32 blocks and Size of user data = 1024 B/ frame

The absolute total overhead, represented by overhead bitrate OHBR is given by the following equation:

$$OHBR = \frac{OH_{ABS}}{N_{frames} \times FD} \qquad \textbf{(17)}$$

where OH_{ABS} presents the absolute value of the overhead over all frames, N_{frames} is the total number of considered frames and FD is the frame duration (WiMAX defines values [IEEE802.16e]: FD ∊ {2; 2.5; 4; 5; 8; 10; 12.5 ; 20}).

The absolute total overhead for BLER=0% per 5000 frames corresponds to the value marked in figures with bold font. This value is approximately 508 kbytes (4064 kbits) per 5000 frames while ARQ_Block_Size is 16 bytes. Hence, if we assume FD = 2ms we can achieve an increase in uplink throughput approximately 406 kbps. The maximum downlink throughput for that scenario (1024 bytes/8192 bits per frame and 2 ms frame duration) is approximately 4096 kbps. Assuming a symmetrical service with 1024 bytes granted in each frame in uplink as well as in downlink, all proposals leads to the overhead reduction roughly 10%. If we consider the size of each ARQ block equal or higher than 64 bytes, the byte saving is approximately 273 kbytes (2184 kbits). In this case it corresponds to 218 kbps bitrate. The maximum user data throughput is roughly 4000 kbps (1024 bytes/8192 bits per frame and 2 ms frame) which results in 5.5% saving of user's data throughput.

The overhead reduction of ARQ scheme III in comparison with the conventional ARQ for different block sizes is depicted in Figure 27 (selective ACK) and Figure 28 (cumulative ACK). Both figures present the results while user sent 1024 bytes in each frame and PDU contains one block. In case of Figure 29 and Figure 30, the frame size is set to 4096 bytes and PDU = 4 blocks. The proposed ARQ scheme III provides a significant overhead reduction (up to 100%) comparing to the conventional ARQ. The proposal can cause a small increase of the overhead, but only for extremely high values of BLER and specific ARQ_Block_Size. However in these cases the overhead increase is only marginal.

For the scenario with selective ACK, the overhead reduction shows better performance for the lower BLER and high ARQ_Block_Size except for the combination of very high BLER (over 10%) and low ARQ_Block_Size. In this case the proposal performs slightly worse than the conventional ARQ. The better performance of the proposal III is apparent especially for very low BLER and high ARQ_Block_Size.

The cumulative ACK results show the highest overhead reduction for low BLER level. The increasing ARQ_Block_Size decreases ARQ overhead reduction effect of proposals in case of combination of low BLER level and low ARQ_Block_Size. With an increase of BLER level, the proposal shows better results for higher ARQ_Block_Size. The results of the overhead reduction for different BLER converge close to each other for higher ARQ_Block_Size. The positive impact of proposal is decreasing with the increasing number of blocks in a PDU (compare Figure 27 with Figure 29 or Figure 28 with Figure 30).

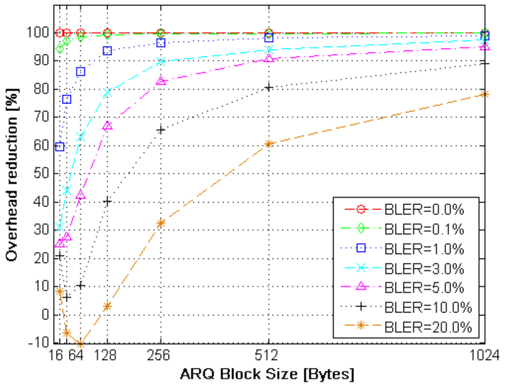


Figure 27: ARQ Overhead reduction vs. ARQ_Block_Size using selective ACK, PDU Size = 1 block and Size of user data = 1024 B/ frame

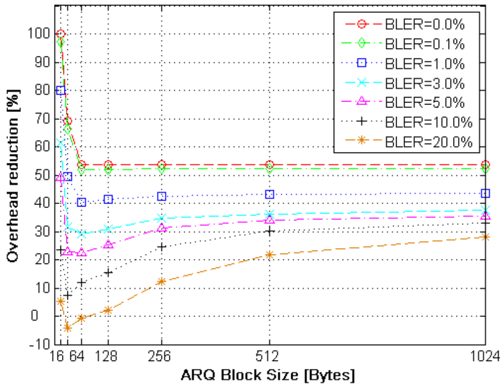


Figure 28: ARQ Overhead reduction vs. ARQ_Block_Size using cumulative ACK, PDU Size = 1 block and Size of user data = 1024 B/ frame

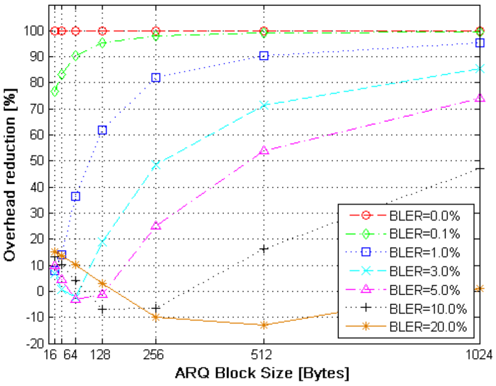


Figure 29: ARQ Overhead reduction vs. ARQ_Block_Size using selective ACK, PDU Size = 4 block and Size of user data = 4096 B/ frame

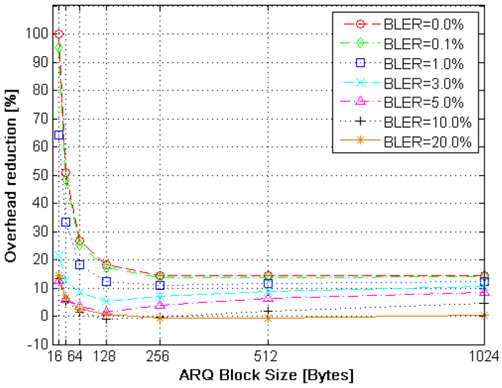


Figure 30: ARQ Overhead reduction vs. ARQ_Block_Size using cumulative ACK, PDU Size = 1 block and Size of user data = 4096 B/ frame

2.4.4 Impact of proposed schemes on overhead for scenario including RS

The simulation focuses on the evaluation of overhead generated by the ARQ procedure in the uplink direction by one user over 2 and 3 hops (see Figure 18).

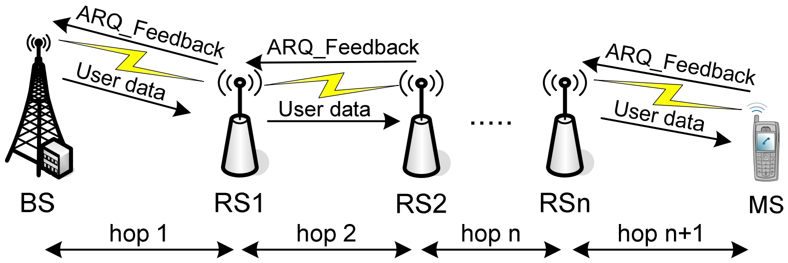


Figure 31: Link level simulation scenario

At the beginning of the simulation, all simulation and link parameters are set up according to values mentioned in Table 10.

Table 10: Simulation parameters for scenario with RSs

Parameter	Value
Number of frames	5 000
BLER per hop [%]	0 – 10
Number of hops	2, 3
ARQ_Block_Size [bytes]	16 – 1024
PDU size [blocks]	1 – 32
ACK Types	Selective, Cumulative
Size of data in each DL frame [bytes]	1024, 4096

Each packet is transmitted over particular hops. The probability of block error is the same over all hops. Therefore, the overall BLER of all hops (between the MS and the BS) can be calculated according to the following formula:

$$BLER_{MS-BS} = \left(1 - BLER_{hop}\right)^{N_{hops}} \qquad \textbf{(18)}$$

where $BLER_{hop}$ represents a BLER over a particular hop and N_{hops} is a number of overall hops between the MS and the BS.

The evaluation is performed for BLER up to 10% per one hop as the BLER of overall path from the MS to the BS is significantly increasing with rising number of hops (see Equation (18)). The BLER of whole path from the MS to the BS is 19% and 27% for two and three hops respectively if 10% BLER per hop is considered.

For more precise evaluation, the overhead of upper layer is also considered. The TCP protocol is assumed for an error correction by upper layer.

2.4.4.1 Results

The results presented in Figure 32 – Figure 39 shows the impact of number of hops on the overhead for various set of ARQ_Block_Size and PDU Size and for all proposed schemes of ARQ. All figures show similar behaviour as scenarios without RSs as presented in previous section. Lowering of the overhead reduction ratio by rising of the number of hops can be observed by comparison of figures for 2 and 3 hops. The best performance is achieved by proposal III. The efficiency of this proposal is rising with increasing number of ARQ_Block_Size; however higher number of hops generally leads to the reduction of its efficiency.

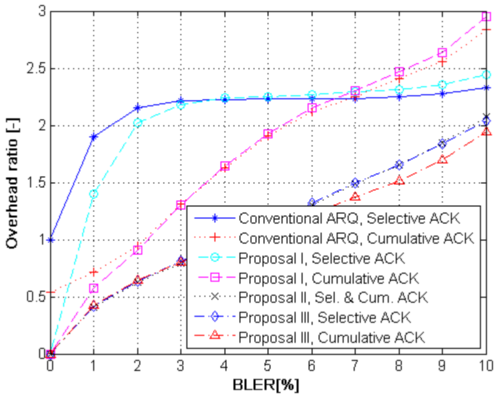


Figure 32: ARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 1 block and Size of user data = 1024 B/frame, 2 hops

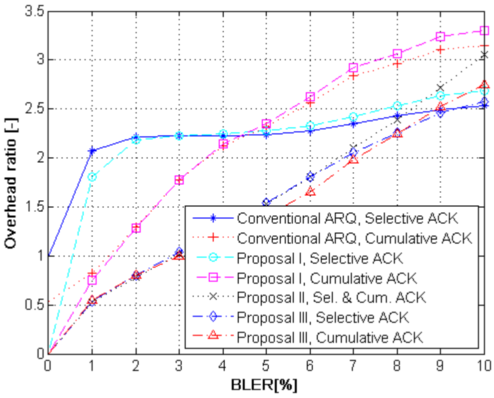


Figure 33: ARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 1 block and Size of user data = 1024 B/frame, 3 hops

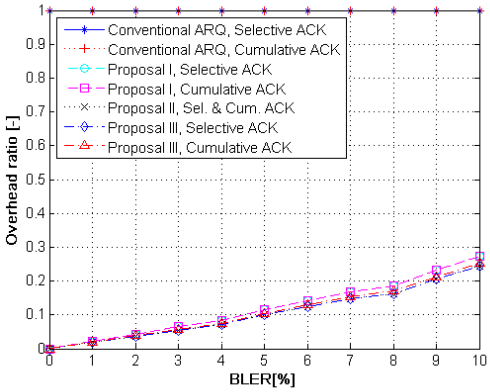


Figure 34: ARQ Overhead vs. BLER for ARQ_Block_Size = 1024 B, PDU Size = 1 block and Size of user data = 1024 B/ frame, 2 hops

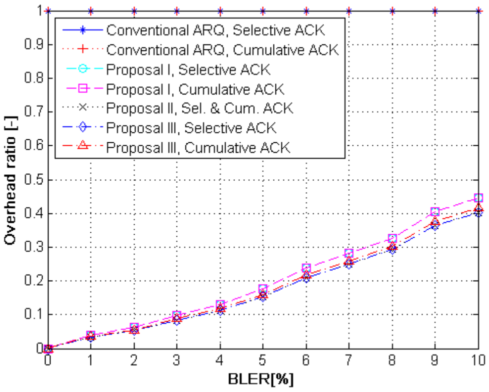


Figure 35: ARQ Overhead vs. BLER for ARQ_Block_Size = 1024 B, PDU Size = 1 block and Size of user data = 1024 B/ frame, 3 hops

If the small PDU Sizes are considered, the proposed scheme III with selective ACK performs significantly better than conventional one for lower level of BLER. On the other hand, the proposed scheme outperforms the conventional ARQ more significantly for higher BLER levels if the high PDU Size is used. For cumulative ACK, the efficiency of the proposal III is more noticeable for very low and higher levels of BLER.

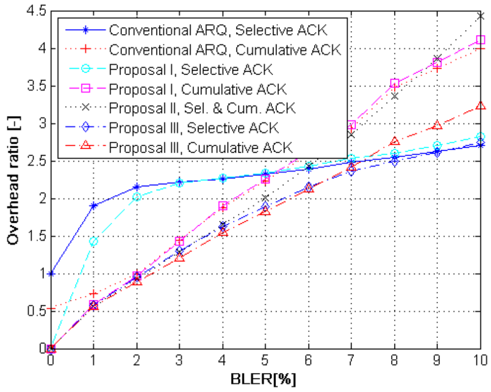


Figure 36: ARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 2 block and Size of user data = 1024 B/frame, 2 hops

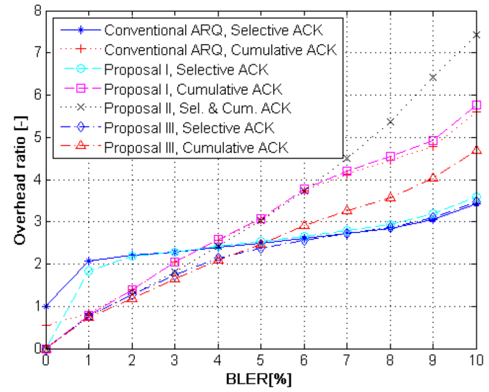


Figure 37: ARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 2 block and Size of user data = 1024 B/frame, 3 hops

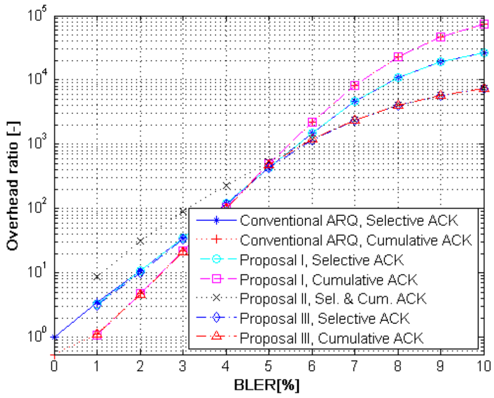


Figure 38: ARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 32 block and Size of user data = 1024 B/ frame, 2 hops

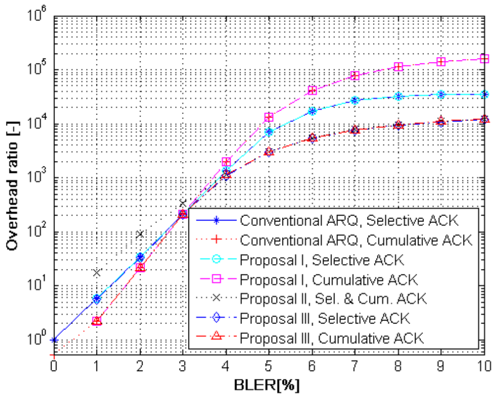


Figure 39: ARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 32 block and Size of user data = 1024 B/ frame, 3 hops

The overhead reduction of ARQ scheme III in comparison with the conventional ARQ for different block sizes is depicted in Figure 40 - Figure 43 (selective ACK) and Figure 44 - Figure 47 (cumulative ACK). Figures present the results while user sent 1024 or 4096 bytes in each frame and the PDU contains 1 or 4 block respectively. The proposed ARQ scheme III provides a significant overhead reduction (up to 100%) comparing to the conventional ARQ. The proposal can cause an increase of the overhead, especially while higher PDU Size and selective ACK are considered. The cumulative ACK results into negligible rise of the overhead only for high BLER simultaneously with low ARQ_Block_Size (32 - 128 depending on PDU Size). The proposed scheme III leads to the significant reduction of overhead for all scenarios with ARQ_Block_Size equal to 16 bytes (between 15% and 100%). Moreover, the ACK type does not influence neither network throughput nor packet delay. Hence, the proposal can reduce management overhead for all combination of BLER, ARQ_BLOCK_Size and PDU Size.

The communication over more hops lowers the overhead reduction efficiency of the proposal III. This fact is more noticeable for selective ACK, higher PDU Size and higher BLER (e.g. the number of hops nearly does not influence the reduction ratio for cumulative ACK and PDU Size equal to 4 blocks). The results of ARQ with selective ACK are depicted in Figure 40 – Figure 43.

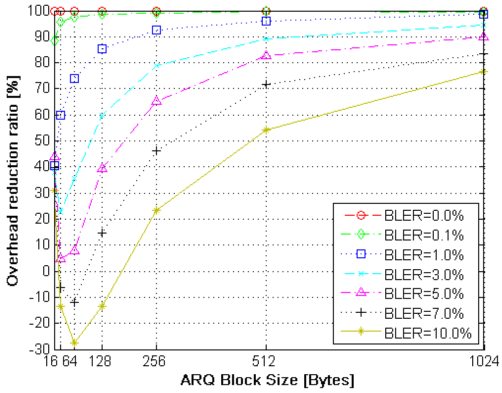


Figure 40: ARQ Overhead reduction vs. ARQ_Block_Size using selective ACK, PDU Size = 1 block and Size of user data = 1024 B/ frame, 2 hops

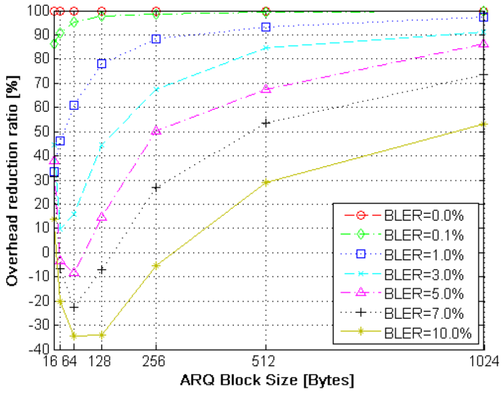


Figure 41: ARQ Overhead reduction vs. ARQ_Block_Size using selective ACK, PDU Size = 1 block and Size of user data = 1024 B/ frame, 3 hops

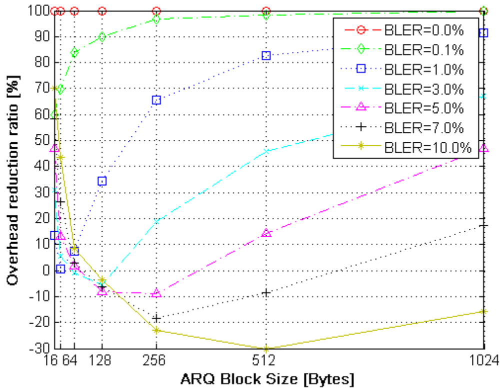


Figure 42: ARQ Overhead reduction vs. ARQ_Block_Size using selective ACK, PDU Size = 4 block and Size of user data = 4096 B/ frame, 2 hops

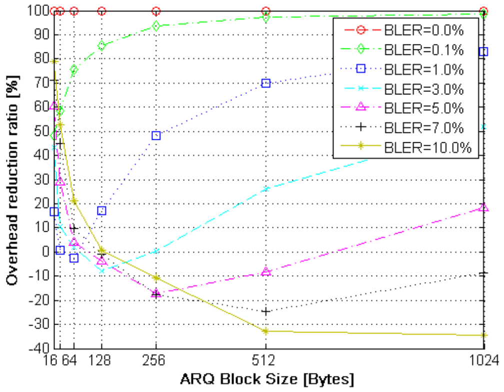


Figure 43: ARQ Overhead reduction vs. ARQ_Block_Size using selective ACK, PDU Size = 4 block and Size of user data = 4096 B/ frame, 3 hops

The consequent figures (Figure 44 – Figure 47) presents the results obtained for cumulative ACK.

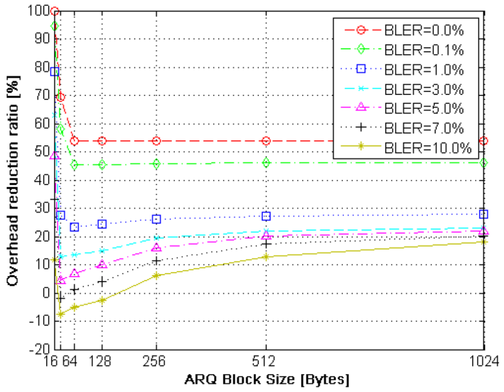


Figure 44: ARQ Overhead reduction vs. ARQ_Block_Size using cumulative ACK, PDU Size = 1 block and Size of user data = 1024 B/ frame, 2 hops

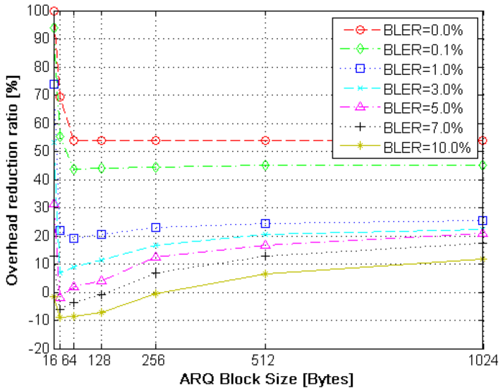


Figure 45: ARQ Overhead reduction vs. ARQ_Block_Size using cumulative ACK, PDU Size = 1 block and Size of user data = 1024 B/ frame, 3 hops

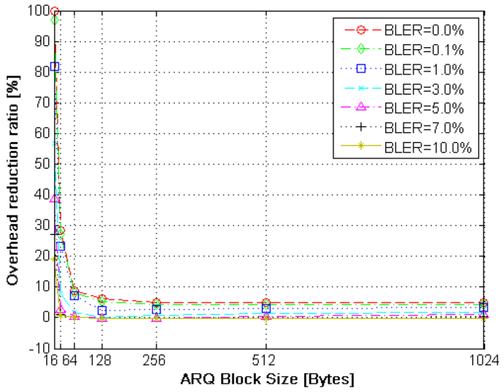


Figure 46: ARQ Overhead reduction vs. ARQ_Block_Size using cumulative ACK, PDU Size = 4 block and Size of user data = 4096 B/ frame, 2 hops

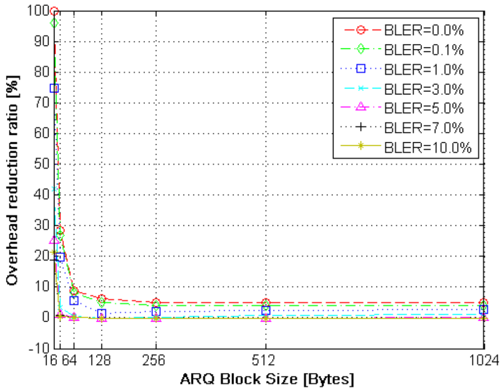


Figure 47: ARQ Overhead reduction vs. ARQ_Block_Size using cumulative ACK, PDU Size = 4 block and Size of user data = 4096 B/ frame, 3 hops

2.4.5 Impact of ARQ and HARQ on the overhead

In conventional way, the ARQ and HARQ work independently on each other [IEEE802.16e]. The HARQ provides most of the radio link error detection and correction. However, due to the limitation of a number of retransmission, some data can be still not delivered without errors by using HARQ. These data are retransmitted by ARQ process. The conventional ARQ process has to ACK or NACK all data independently on the result of HARQ procedure. While both ARQ and HARQ are utilized and the interaction between their control entities enables to inform ARQ entity on results of the HARQ process, the overhead can be significantly reduced (see e.g. [Maheshwari2008]). The mutual interaction is based on the exchange of information on successful transmission of packets from HARQ entity to the ARQ entity. Therefore, the data confirmed by HARQ cannot be furthermore confirmed by ARQ process.

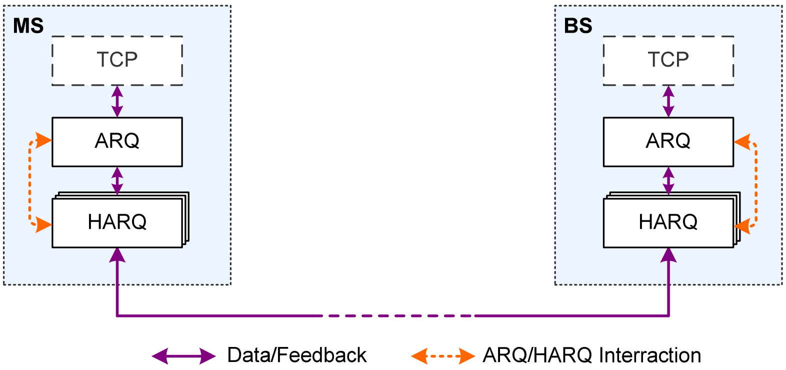


Figure 48: Principle of ARQ/HARQ cooperation

The scenario with conventional ARQ and HARQ with and without interaction, ARQ proposed scheme III with HARQ with and without interaction are considered for evaluation. Similar parameters as in the evaluation of standalone ARQ are considered. The list of all important parameters is presented in Table 11.

Table 11: Simulation parameters for ARQ+HARQ

Parameter	Value
Number of frames	2000
BLER per hop [%]	0 – 10
Number of hops	1, 3
ARQ_Block_Size [bytes]	16 – 1024
PDU size [blocks]	1 – 16
ARQ ACK Types	Selective, Cumulative
Max. HARQ retransmissions	2, 4
HARQ Type	CC, IR-CTC
HARQ packet/burst size	1 PDU
Size of data in each DL frame [bytes]	1024

The maximum number of HARQ retransmissions is set to 2 and 4. Both types of HARQ, Chase Combining (CC) and Incremental Redundancy (IR) are considered in evaluations. The Convolutional Turbo Code (CTC) is considered in evaluation if IR HARQ is performed.

The overhead produced by HARQ depends on the HARQ Type as follows. Firstly, the acknowledgment of HARQ bursts by modification of AI_SN (HARQ Identifier Sequence Number) of appropriate ACID (HARQ Channel ID) is assumed. The AI_SN is included in HARQ DL or UL maps (see [IEEE802.16e]). The size of HARQ map can be described by the consequent formula:

$$HARQOH_{DL} = \begin{cases} 64 + SubB + res \;\ldots Re\,gionID\_ON \\ 40 + SubB + res \ldots Re\,gionID\_OFF \end{cases}$$

$$HARQOH_{UL} = \begin{cases} 48 + SubB + res \;\ldots Re\,gionID\_ON \\ 24 + SubB + res \ldots Re\,gionID\_OFF \end{cases} \tag{19}$$

where *SubB* is a size of management overhead according to a sub-burst. The amount of management overhead depends also on the utilization of Region ID (see [IEEE802.16e]). In the simulations, the Region ID is not considered. The actual amount of bits of SubB depends on the HARQ Type. Based on the [IEEE802.16e], the size of message according to the sub-bursts is following:

$$\begin{aligned} SubB_{CC} &= 8 + N_{sub} \times (RCID + 20 + DIUC) \\ SubB_{IR-CTC} &= 8 + N_{sub} \times (RCID + 20) \\ SubB_{IR-CC} &= 8 + N_{sub} \times (R + 22 + DIUC) \end{aligned} \tag{20}$$

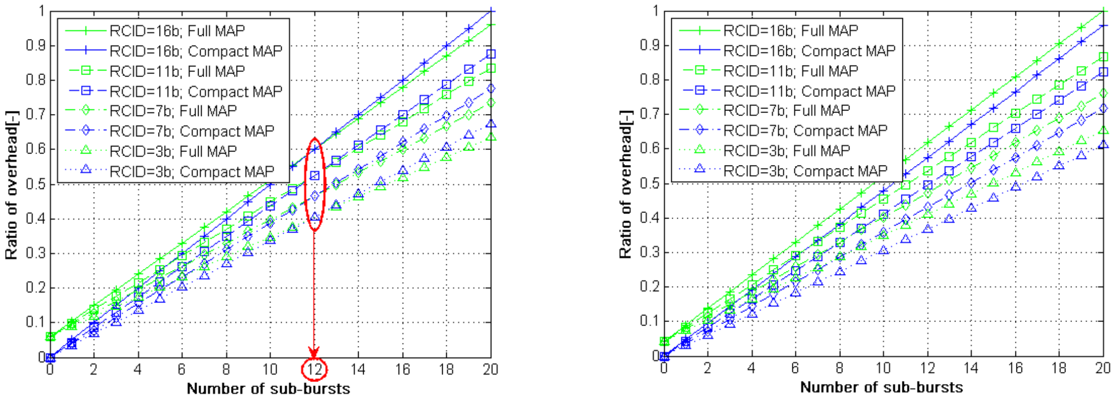
where N_{sub} is a number of sub-bursts; *RCID* represents a size of Reduced CID (in the simulations, 7 bits RCID is considered); and *DIUC* represents the size of optional field denoted DIUC containing 8 bits if it is included.

For the case when a low number of bursts are transmitted within a frame, the utilization of Compact HARQ DL/UL maps enables to reduce an overhead. The overhead generated by compact version of maps is not dependent on the HARQ type. The amount of overhead can be expressed by the next equation:

$$\begin{aligned} HARQOHcomp_{DL} &= 12 + RCID + HCI + CCI \\ HARQOHcomp_{UL} &= 12 + RCID + HCI \end{aligned} \tag{21}$$

where *HCI* is a size of HARQ control IE (8 bits if HARQ is enabled and 4 bits if HARQ is temporary disabled); *CCI* is a size of CQICH control IE (16 bits if CQICH information are included and 4 bits if the information are not included).

The simple evaluation of equations for full and compact HARQ maps enable to determine which kind of maps results into minimum management overhead over the number of HARQ sub-bursts (see Figure 49). As the results show, the compact version of maps is profitable for all numbers of sub-bursts in UL as well as for up to 12 sub-bursts in DL over all length of Reduced CID. This result is assumed in the further evaluations.



(a) (b)

Figure 49: Comparison of the overhead generated by compact and full HARQ maps for DL (a) and UL (b)

The relation between BLER (for ARQ confirmation) and PER (for HARQ confirmation) is defined (according to [Provvedi2004]) by following equation:

$$PER = 1 - (1 - BLER)^{N_{blocks}} \tag{22}$$

where N_{blocks} is a number of block embedded in a packet.

2.4.5.1 Results

The results are separated into several groups according to the number of hops (left-hand and right-hand figures corresponds to one and three hops respectively), HARQ Type (CC HARQ in Figure 50 - Figure 61; IR-CTC in Figure 62 - Figure 73) and maximum number of HARQ retransmissions for higher clarity. The figures are grouped into set of 6 figures with the same HARQ Type, with the same maximum number of retransmissions and with varying number of hops, ARQ_Block_Size and PDU Size.

Each figure shows the result of overhead generated due to ACK/NACK of all frames by HARQ/ARQ. The expressed overhead is relative to the overhead generated by conventional IEEE802.16e ARQ (in figures noted as *Conv. ARQ*) using Selective ACK (in figures marked as *SACK*) together with HARQ while no interaction between both is considered. The cumulative ACK (*CACK*) is also taken into account in figures. All figures also depict results for both techniques while interaction is not enabled (without interaction - in figures denoted *w/o int.*) and while the interaction is enabled (with interaction - in figures noted as *w int.*). The overhead for the same cases is presented also if HARQ and proposed innovation of ARQ scheme III (in figures *ARQ PIII*) are simultaneously utilized.

As can be observed from Figure 50 - Figure 73, the scenario where ARQ and HARQ interact outperforms all other scenarios. Minor improvement is achieved by using proposal III instead of conventional ARQ. However, this improvement is noticeable only as long as ARQ_Block_Size is low (e.g. 16 bytes), PDU Size is higher (e.g. 16 blocks) and mutual interaction of ARQ and HARQ is considered.

While no interaction between HARQ and ARQ entities is enabled, the difference between ARQ and proposal III is more significant. The reduction of overhead is more appreciable for lower number of hops or higher ARQ_Block_Size. The improvement achieved by ARQ proposal III in comparison to scenario using conventional ARQ without interaction is due the fact that the ARQ scheme III generates lower overhead while the packet are delivered without errors.

The first group of figures represent the results of CC HARQ for maximum four HARQ retransmissions.

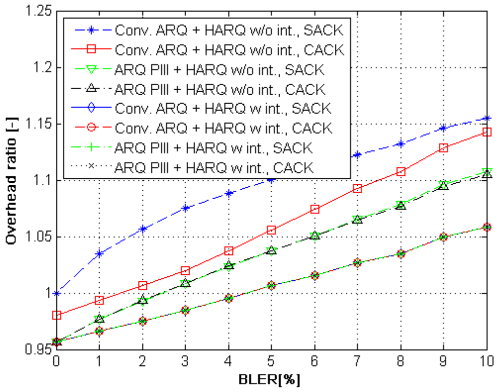


Figure 50: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 1 hop, max four HARQ retrans., HARQ Type: CC

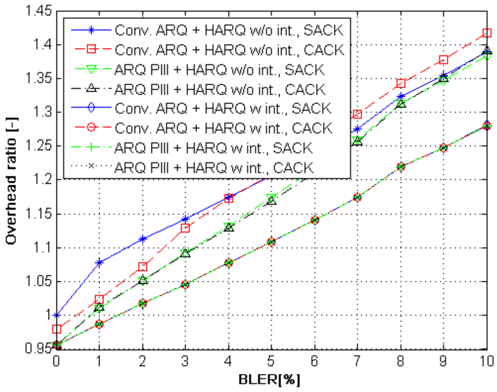


Figure 51: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 3 hops, max four HARQ retrans., HARQ Type: CC

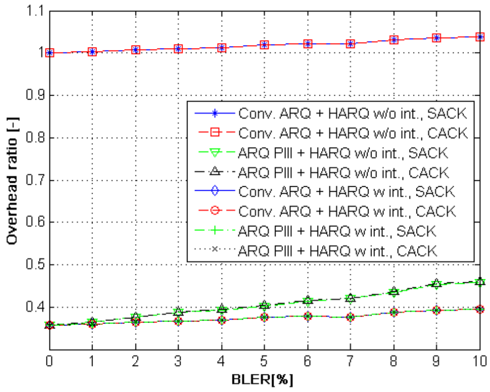


Figure 52: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 1024 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 1 hop, max four HARQ retrans., HARQ Type: CC

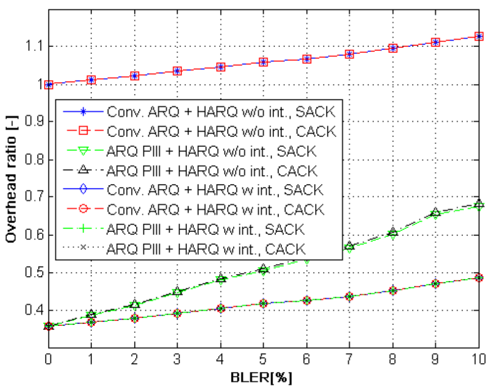


Figure 53: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 1024 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 3 hops, max four HARQ retrans., HARQ Type: CC

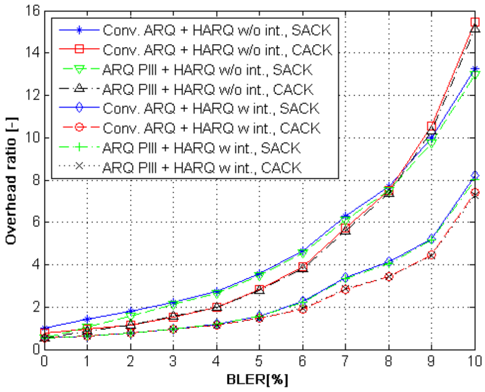


Figure 54: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 16 block, Size of user data = 1024 B/frame, 1 hop, max four HARQ retrans., HARQ Type: CC

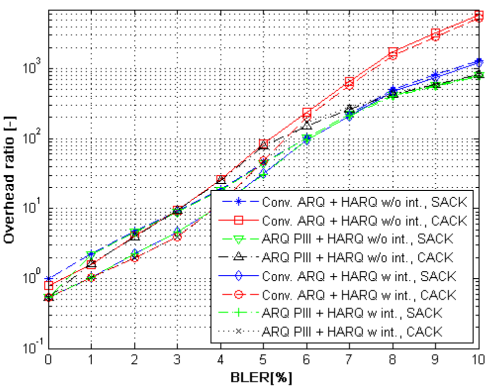


Figure 55: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 16 block, Size of user data = 1024 B/frame, 3 hops, max four HARQ retrans., HARQ Type: CC

The next group of figures show the results of CC HARQ for maximum two HARQ retransmissions.

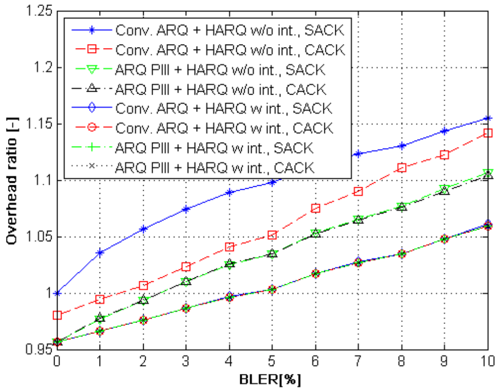


Figure 56: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 1 hop, max two HARQ retrans., HARQ Type: CC

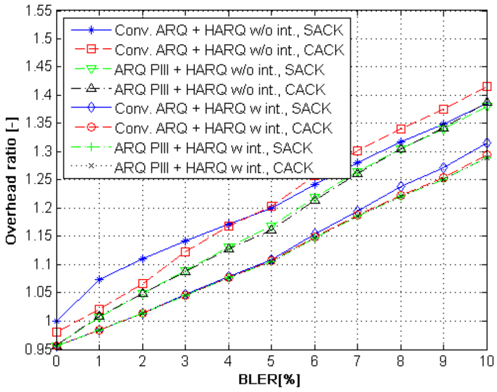


Figure 57: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 3 hops, max two HARQ retrans., HARQ Type: CC

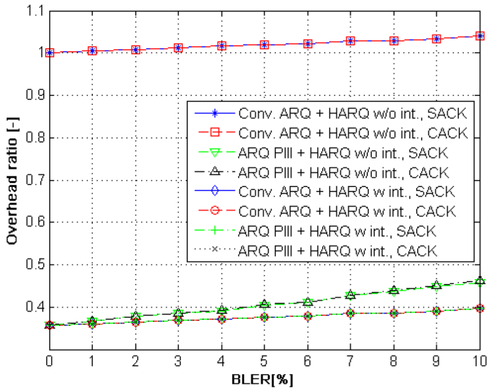


Figure 58: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 1024 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 1 hop, max two HARQ retrans., HARQ Type: CC

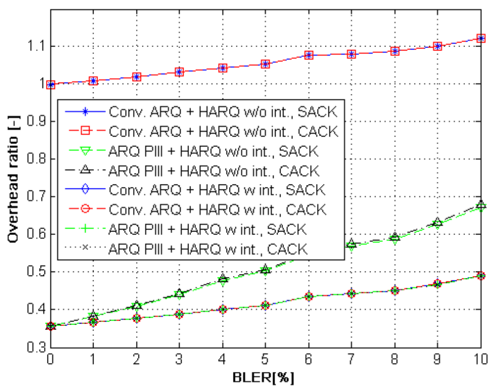


Figure 59: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 1024 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 3 hops, max two HARQ retrans., HARQ Type: CC

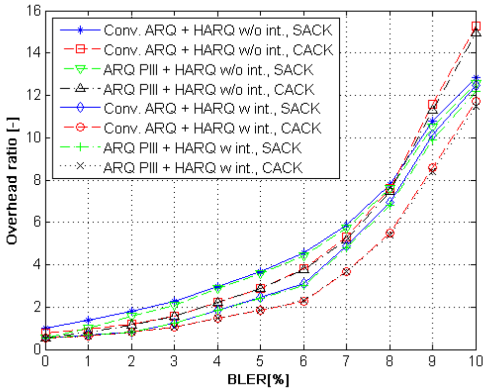


Figure 60: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 16 block, Size of user data = 1024 B/frame, 1 hop, max two HARQ retrans., HARQ Type: CC

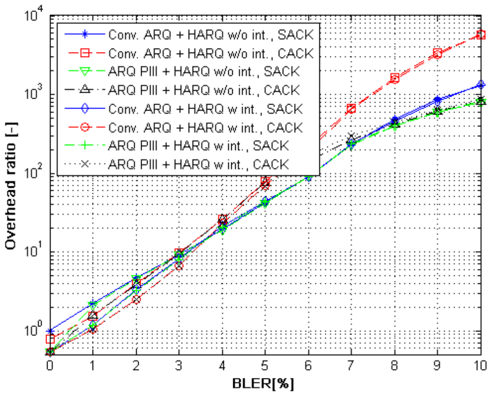


Figure 61: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 16 block, Size of user data = 1024 B/frame, 3 hops, max two HARQ retrans., HARQ Type: CC

The following group of figures represent the results of IR_CTC HARQ for maximum four HARQ retransmissions.

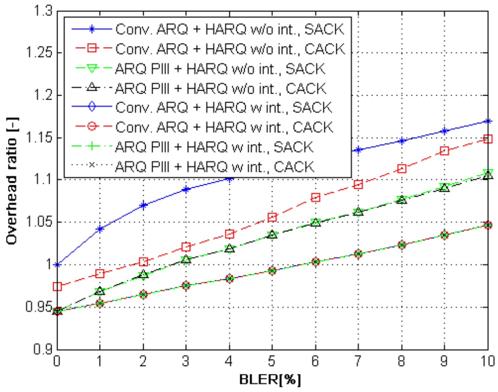


Figure 62: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 1 hop, max four HARQ retrans., HARQ Type: IR-CTC

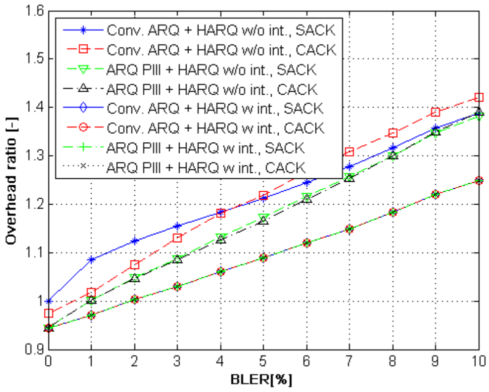


Figure 63: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 3 hops, max four HARQ retrans., HARQ Type: IR-CTC

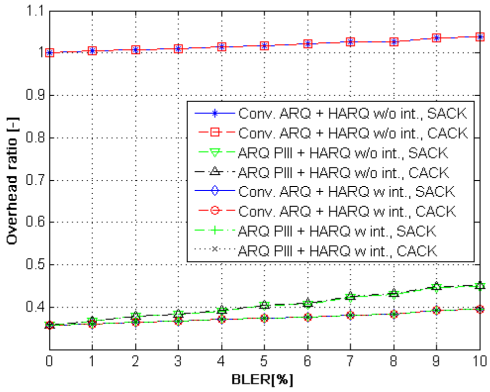


Figure 64: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 1024 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 1 hop, max four HARQ retrans., HARQ Type: IR-CTC

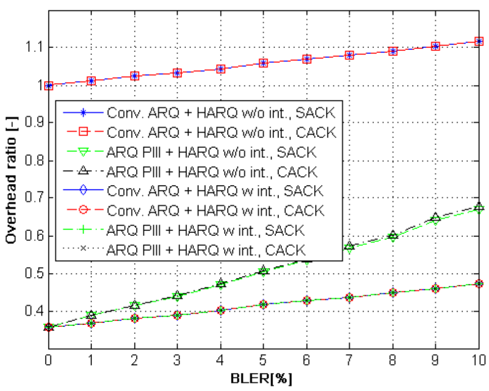


Figure 65: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 1024 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 3 hops, max four HARQ retrans., HARQ Type: IR-CTC

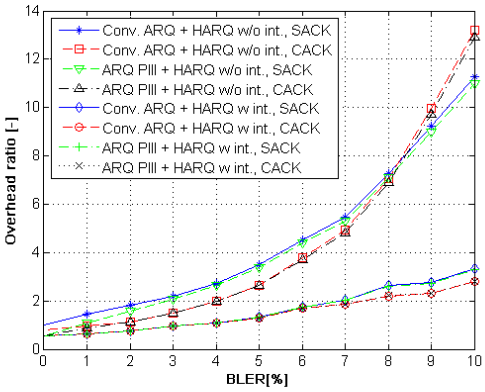


Figure 66: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 16 block, Size of user data = 1024 B/frame, 1 hop, max four HARQ retrans., HARQ Type: IR-CTC

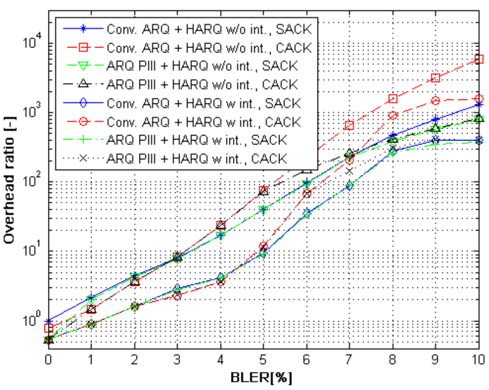


Figure 67: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 16 block, Size of user data = 1024 B/frame, 3 hops, max four HARQ retrans., HARQ Type: IR-CTC

The last group of figures represent the results of IR_CTC HARQ for maximum two HARQ retransmissions.

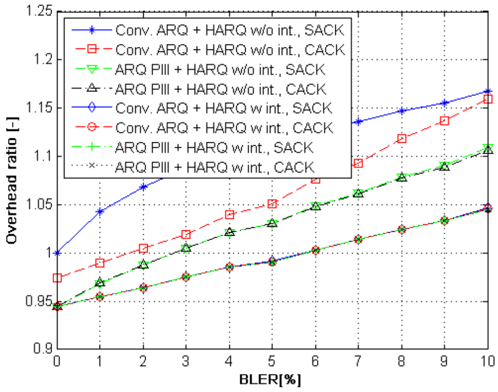


Figure 68: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 1 hop, max two HARQ retrans., HARQ Type: IR-CTC

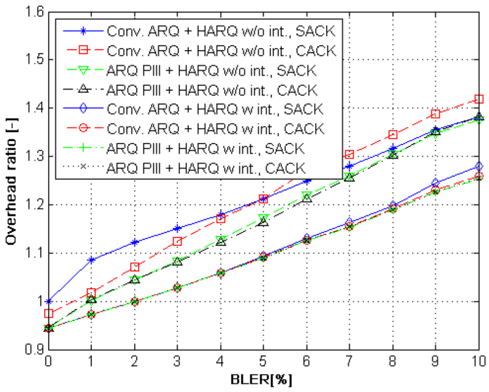


Figure 69: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 3 hops, max two HARQ retrans., HARQ Type: IR-CTC

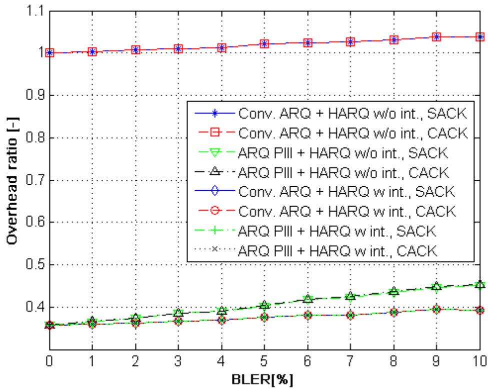


Figure 70: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 1024 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 1 hop, max two HARQ retrans., HARQ Type: IR-CTC

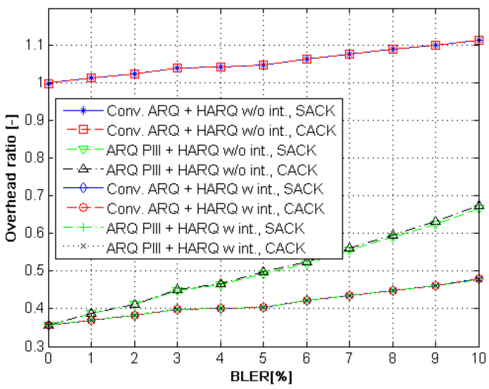


Figure 71: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 1024 B, PDU Size = 1 block, Size of user data = 1024 B/frame, 3 hops, max two HARQ retrans., HARQ Type: IR-CTC

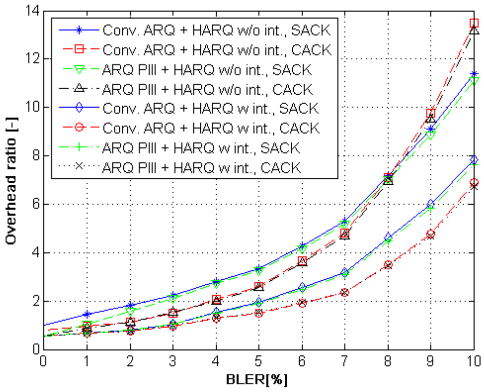


Figure 72: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 16 block, Size of user data = 1024 B/frame, 1 hop, max two HARQ retrans., HARQ Type: IR-CTC

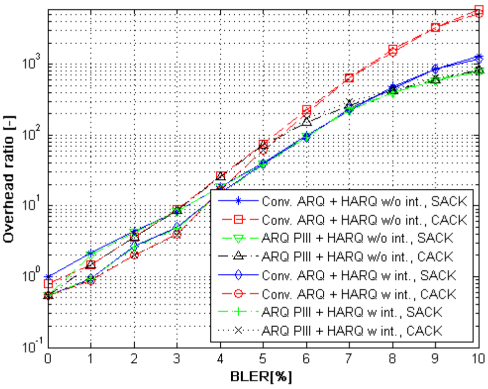


Figure 73: ARQ & HARQ Overhead vs. BLER for ARQ_Block_Size = 16 B, PDU Size = 16 block, Size of user data = 1024 B/frame, 3 hops, max two HARQ retrans., HARQ Type: IR-CTC

The impact of individual parameters observed from previous figures on the efficiency of overhead reduction can be summarized into the following conclusions:

- **Number of Hops**: the efficiency of proposal III is decreasing with higher number of hops if no interaction is considered; however the reduction of the overhead is not influenced by a number of hops if interaction is enabled.
- **ARQ_Block_Size**: the more significant reduction of overhead is achieved by utilization of proposal III with HARQ even without interaction for higher ARQ_Block_Size; additional reduction of overhead by increase of this parameter is enabled by the interaction for both conventional ARQ as well as for ARQ proposal III; the level of this additional reduction is getting higher with BLER since the higher BLER increases the amount of packets not corrected by HARQ.
- **PDU Size**: the overall overhead of ARQ and HARQ rises considerably with PDU as more blocks have to be corrected by ARQ since the probability that certain part of PDU is delivered with errors is increasing as well; however influence of the level of overhead reduction by this parameter is only minor.
- **Maximum number of retransmission**: the impact of a number of retransmissions on the overhead is negligible in most of scenarios; nevertheless the noticeable overhead reduction if four retransmissions occur is achieved only for low ARQ_Block_Size together with high PDU Size when interaction is enabled; the reason is that number of not corrected errors by two retransmissions do not differ to much from four retransmissions, hence the ARQ overhead in similar for both cases.
- **Type of HARQ (CC vs. IR)**: the IR performs slightly better, however the difference in overall overhead between both HARQ types is also negligible instead of scenarios with low ARQ_Block_Size, high PDU_Size and enabled interaction; the reason for this conclusion is the same as explained in the previous bullet.

2.4.6 Conclusion

All proposals reduce the overhead. The overhead saving depends on several parameters such as BLER, ARQ_Block_Size parameter, PDU size and ACK type. The ARQ overhead reduction can reach up to 100% in comparison to the conventional IEEE 802.16e ARQ. Since the ARQ overhead influents the uplink channel throughput in dependence on the downlink channel quality, the throughput in the uplink can be enhanced up to approximately 10% of downlink throughput (e.g., the uplink throughput can be increase for 400 kbps if the user uses 4 Mbps in the downlink) when considering symmetric services.

The increase of a number of hops between a MS and BS leads to the lowering of the overhead reduction efficiency of the proposal III. This fact is more significant for selective ACK, higher PDU Size and higher BLER. At least one ACK type results into reduction of management overhead by proposal III for all combination of BLER, ARQ_BLOCK_Size and PDU Size.

While the HARQ and ARQ are enabled and no mutual interaction between both entities is enabled, the difference between conventional ARQ and proposal III is significant. The exact level of overhead reduction depends heavily on the setting of the ARQ and HARQ parameters. The local interaction between ARQ and HARQ enables additional reduction of the overhead. While interaction is enabled, the significant improvement by using proposal III instead of conventional ARQ is achieved only while ARQ_Block_Size is low, PDU Size is high and while the interaction between ARQ and HARQ is enabled.

3 SYSTEM LEVEL RECONFIGURATION

3.1 Flow control in Relay Enhanced Cells

3.1.1 Goals

In multi-hop transmissions often the link capacities of the different hops of a connection are different and changing over time. Thus, PDUs get dropped at Relay Stations (RSs) if the capacity of the second hop of a connection is lower than that of the first hop, see Figure 74. In this case PDUs that are dropped at the RS have wasted resources on the first hop. One of the goals is to develop a flow control protocol located in the Data Link Layer (DLL) that adapts the data rate of the end-to-end connection to the data rate of the weakest hop. Thus, the overall cell capacity is increased.

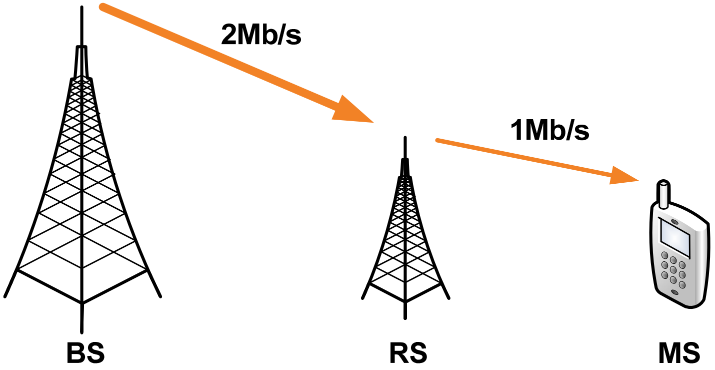


Figure 74: **PDUs are dropped at the RS because the capacity of the second-hop is lower than the capacity of the first hop**

Furthermore, the loss of single PDUs at the RS severely degrades the performance of Transmission Control Protocol (TCP) connections because the combined flow/congestion control mechanism of the TCP reduces the congestion window size each time a PDU gets lost. The flow control mechanism avoids the loss of single PDUs at the RS. Thus, the TCP congestion control mechanism does not need to take action and the data rate of the connection does not drop down.

3.1.2 Concept

Flow Control (FC) can be realized by an explicit FC unit in the DLL. A joint Automatic Repeat reQuest (ARQ)/FC protocol as proposed in many papers such as [Wiemann2005] does not seem to be advantageous over the separated approach because the complexity of the combined ARQ/FC protocol is much higher.

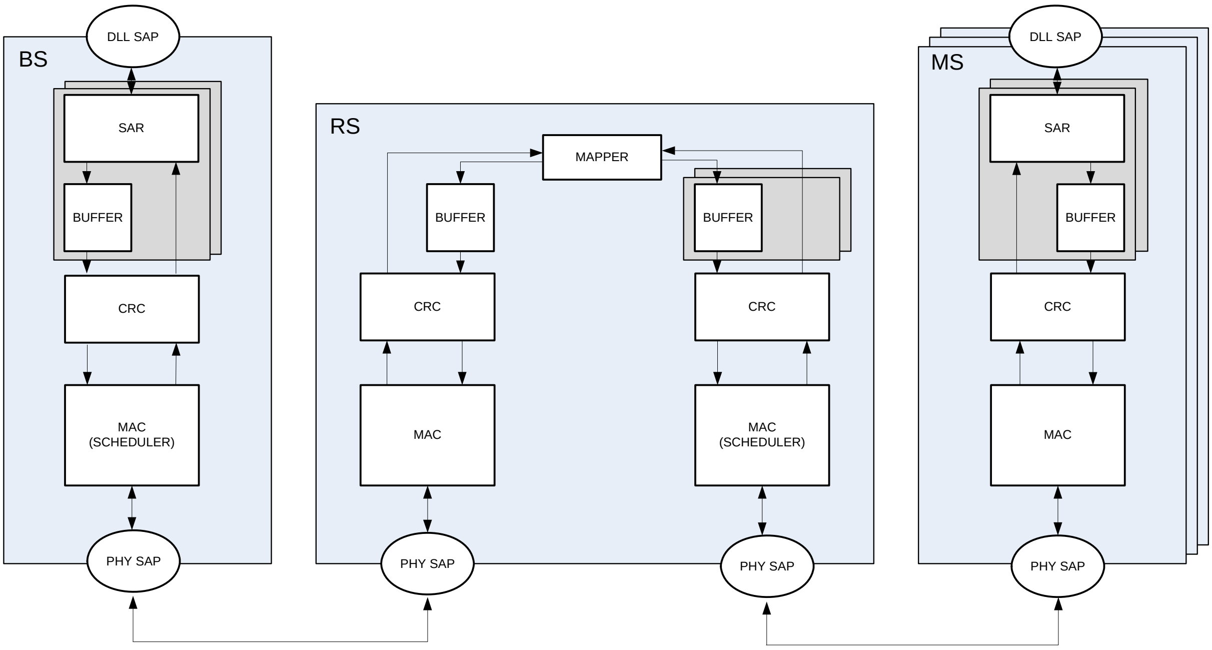


Figure 75: Block diagram of the DLL for a two hop connection

It is expected that one-hop (BS-MS) and two hop (BS-RS-MS) connections will dominate in future IMT-Advanced networks. Therefore, the focus of investigations is set on these types of connections. Anyway, this concept can be easily extended for use in more than two-hop connections. In general, flow control at DLL level is applied only in multi-hop connections as only there the different capacities of the different hops may result in PDUs to be dropped. Hence, two-hop scenarios are considered in the following.

Figure 75 shows a schematic block diagram of the DLL for a two-hop connection. At the BS for each data connection a new instance of a Segmentation And Reassembly (SAR) and a Buffer unit are generated (indicated by the dark grey boxes around these components). Below the Buffer unit there is a single Cyclic Redundancy Check (CRC) unit. As the CRC unit is stateless it is not necessary to create a new instance per connection. All three units together represent the Logical Link Control (LLC) sublayer. In the scheduler at the BS located below the CRC unit all connections are jointly scheduled. In Downlink (DL) direction all PDUs pass these units and are then sent to the according RS. At the RS the PDUs of each connection originating from the BS pass the CRC unit and in case they are error-free are mapped by the Mapper unit to the corresponding second hop connection. The PDUs that shall be forwarded to the MSs are stored in a connection specific Buffer unit. After passing the connection specific ARQ instance and the CRC unit they are scheduled in the Scheduler unit at the RS. At the Mobile Station (MS) all incoming PDUs are delivered to the upper layers after passing the CRC and the connection specific units. In Uplink (UL) direction the PDUs are sent by the MSs to the RS. After passing the connection specific units at the RS (shown on the right side of the RS) the PDUs are again mapped to the corresponding connection on the RS-BS hop and stored in a general, non connection specific buffer. At this place a connection specific buffer is not necessary as long as different Quality of Service (QoS) classes are not considered. In the investigated cases the BS scheduler assigns only a single UL resource to the RS. The RS multiplexes the UL traffic of all connected MSs onto this resource.

In DL direction, incoming PDUs mapped at the Mapper unit are stored in the corresponding connection specific buffer instances. If the capacity of the second hop (RS-MS) is lower than that of the first hop (BS-RS) the corresponding buffer instance fills up and after a while PDUs are dropped. In UL direction, incoming PDUs mapped at the Mapper unit are stored in the non connection specific buffer at the RS. If the capacity of the second hop (RS-BS) is smaller than the sum of the first hop (MS-RS) link capacities of all MSs associated to the RS the buffer fills up. If the buffer is full PDUs are dropped. In both cases, the capacity on the first hop that was used to transmit the PDUs that are dropped is wasted. By avoiding these unnecessary transmissions on the first hop the overall cell capacity can be increased and the unused resources can be allocated for transmission of data for other connections. Additionally, for TCP connections avoiding spurious loss of PDUs also avoids throughput drops due to the TCP congestion control mechanism. In the following different flow control protocols are investigated that aim at reaching this goal.

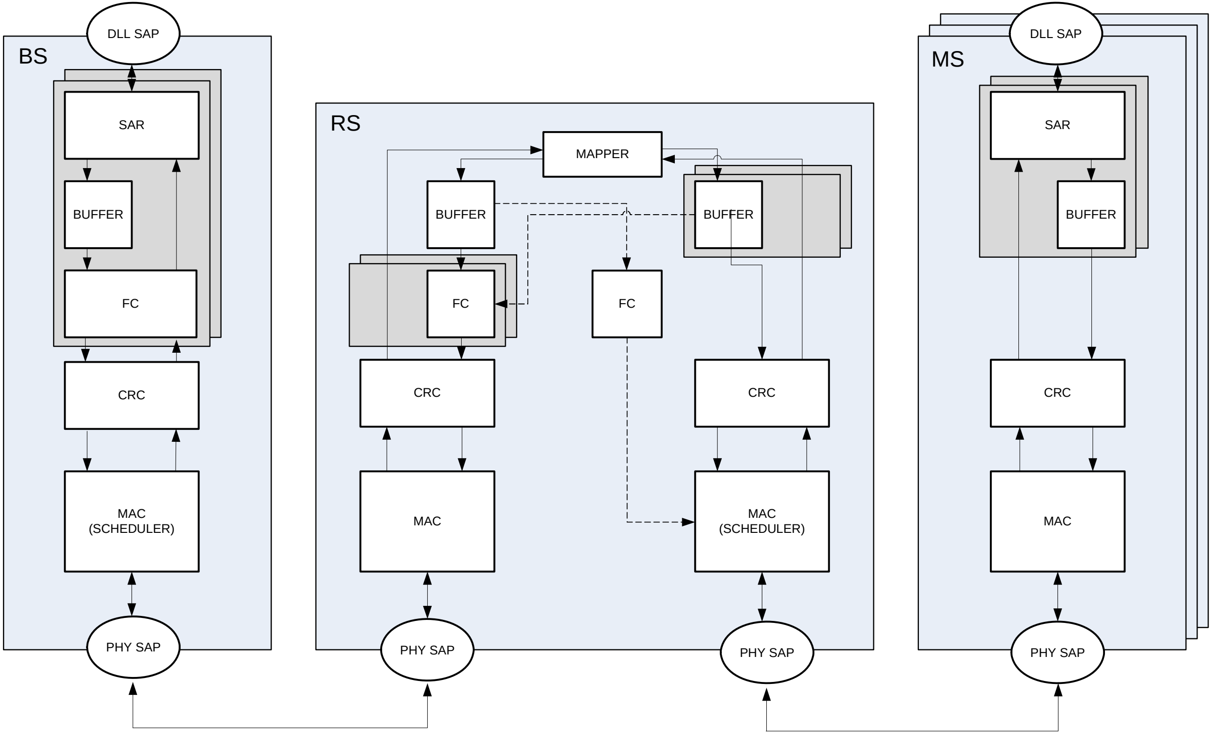


Figure 76: FC with connection based signalling without ARQ

The MAC layer flow control protocol is located in a separate FC unit. It works differently in UL and DL direction. In the following subsections the different flow control mechanisms are described.

3.1.2.1 DL Flow Control

In DL direction overflows may occur only in the buffers at the RS that store PDUs to be sent to MSs as shown in Figure 76. To avoid these overflows the Flow Control (FC) unit at the RS continuously monitors the fill levels of these buffers and signals the results to the BS via the air interface. As the connections on the second hop that are associated to the connections on the first hop may have different Connection Identifiers (CIDs) the FC component maps the CIDs of the connections of the second by means of the Mapper unit to the corresponding CIDs of the first hop. At the BS the FC unit evaluates the received messages and controls the DL scheduler accordingly. The scheduler can be requested to reduce the data rate for a certain connection or not to schedule data traffic for that connection at all. If the fill level of the according buffer at the RS falls below the pre-define threshold the FC unit may signal to the BS to increase the data rate for that connection, again. So, in DL direction the functionality for the flow control mechanism is split over two stations, the BS and the RS. Hence, a signalling over the air is necessary.

The information used by the FC unit to control the scheduler may have different degrees of granularity. In the simplest case only one threshold is defined for the fill level of a buffer. If this threshold is exceeded the flow control unit requests the scheduler not to schedule further data for that connection. If the fill level falls below this threshold, the scheduler may schedule data for that connection, again. Alternatively, two thresholds for the fill level can be set. If the large value is exceeded transmission of data for that connection is interrupted, if the fill level falls below the smaller value transmission of data for that connection is resumed. Furthermore, the current fill level of a buffer may be taken into account for the scheduling to dynamically adapt the data rate.

Depending on the degree of granularity of information the signalling from the RS to the BS for the DL flow control is more or less complex. In case only thresholds are used to determine whether data shall be transmitted or not a simple bit pattern indicating buffer overflows for all CIDs sorted in ascending order is sufficient. So, even for many connections the signalling is very efficient. In case the current fill levels of all buffers should be signalled more data need to be transmitted per connection. The messages may be transmitted periodically or event-based when the fill levels of the buffers change. The periodic signalling has advantages when signalling messages get lost. If the BS is not able to decode the message correctly it waits for the next transmission of that message. In case, the signalling is done event-based a hand-shake mechanism might be necessary to assure the correct reception of the message at the BS. There are two types of signalling mechanisms:

3.1.2.1.1 Connection Based Signalling

The BS downlink traffic can be controlled through insertion of connection specific FC units in the LLC layer of the BS and the RS, as shown in Figure 76. Each instance of the BS FC unit is able to reduce or to stop the DL traffic of its associated connection. The fill level of the connection specific RS DL Buffer unit depends on the system load. Each instance of the Buffer unit sends status information to the according RS FC instance, if the fill level exceeds a defined maximum threshold or falls below a minimum threshold. The RS FC instance generates a control message PDU, which indicates the BS that the downlink traffic rate has to be adapted for the mentioned connection. The signalling effort is high, because every connection has to be signalled individually.

3.1.2.1.2 Map Based Signalling

Instead of integrating the BS FC unit into the BS data flow the BS Remote FC unit can be placed aside and control the BS scheduler via an extra interface as depicted in Figure 77. In that case an out of flow FC DL unit in the RS is used to process the information about the fill levels of the instances of the RS buffer unit and sends them for further processing to the BS Remote FC unit. The information about the fill levels of all connections are transmitted in a single Information Element (IE). Hence, the signalling effort is small.

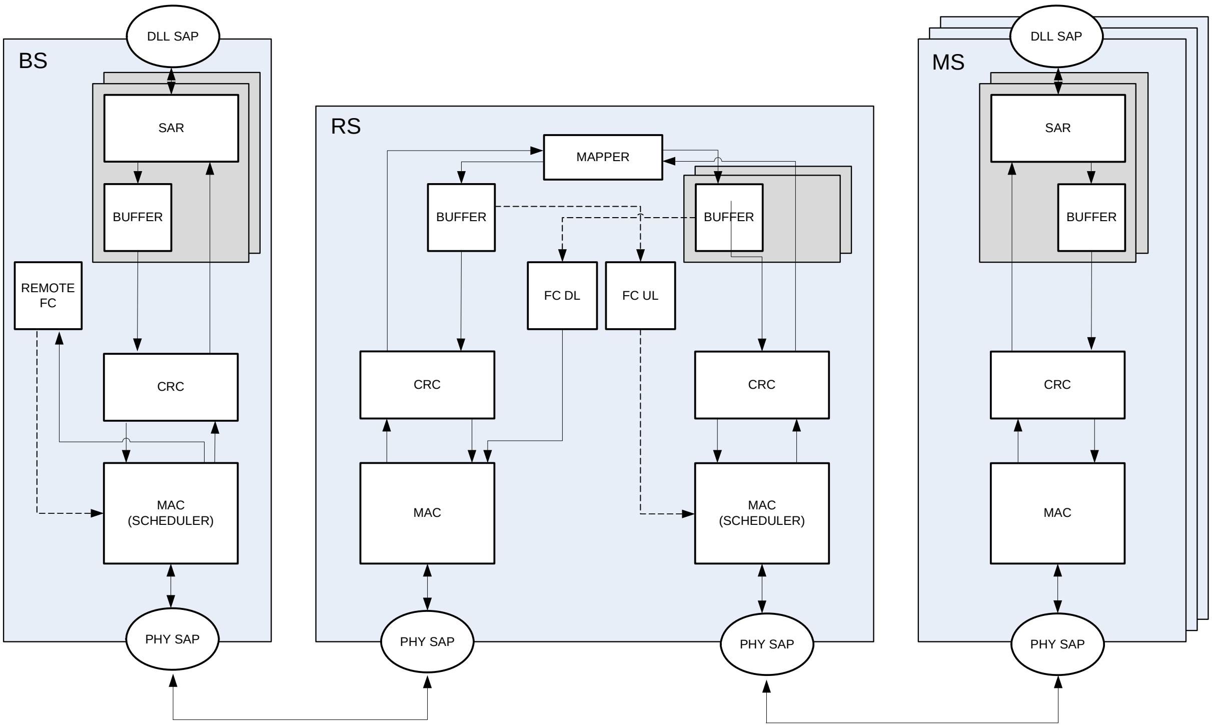


Figure 77: FC with map based signalling without ARQ

3.1.2.2 UL Flow Control

In UL direction overflows may occur only in the non connection specific buffer unit at the RS storing PDUs to be sent to the BS. The UL Flow Control (UL FC) unit continuously monitors the fill level of that buffer. If the fill level exceeds the pre-defined threshold the UL FC unit requests the scheduler at the RS that schedules the UL traffic from the MS to the RS to reduce the data rates for all MS to RS connections. But unlike in DL direction no flow control information need to be transmitted via the air interface. The FC unit responsible for the flow control in UL direction is directly connected to the buffer that is monitored and to the RS scheduler. Therefore, no distinction between different signalling types is necessary in UL direction. Furthermore, as control messages cannot get lost the event-based control of the RS scheduler is recommended.

3.1.2.3 Combination of FC and ARQ mechanisms

Often flow control is closely combined with an ARQ mechanism because it is assumed that an ARQ mechanism inherently provides flow control. But this is not true. An ARQ unit generates an ACK/NACK message to signal its peer entity that the PDU has been correctly received or has to be retransmitted. In case an ACK is received the ARQ unit cancels the corresponding resend timeout. If the ARQ unit delays the transmission of an ACK message to control the traffic flow for that connection it could be possible that the according resend timer in the peer entity fires. Then, a PDU that has been correctly received is retransmitted. So, another type of message is necessary to signal the peer entity that no further PDUs shall be sent even if previous PDUs has been correctly received. Alternatively, the peer entity may only send further PDUs on request. This approach is proposed in [Wiemann2005]. But if different messages are used for the ARQ mechanism and the flow control to signal different information it is possible to split the functionality into separate ARQ and FC units. In the following some possible combinations of ARQ mechanisms and flow control are presented where the functionality is split into two separate units.

3.1.2.3.1 Combination of FC and Hop-by-Hop ARQ

A hop-by-hop ARQ is used to guarantee the correct reception of PDUs at the destination of that hop. In case of a Relay Enhanced Cell (REC) as assumed in the investigations there are two independent hops per connection and hence also two independent pairs of ARQ units as shown in Figure 78. This configuration of ARQ units can only recognize and correct the loss of PDUs due to transmission errors. The loss of PDUs due to a buffer overrun cannot be detected as the PDU drops happen outside the scope of the two ARQ pairs. Hence, an additional FC protocol is necessary to assure that no PDUs get lost in the end-to-end connection. As mentioned previously there are two different methods to signal the FC in DL direction, connection and map based. Both methods can be combined with a hop-by-hop ARQ mechanism as shown in Figure 78 and Figure 79. In case hop-by-hop ARQs are used the FC units at the RS need to know the fill levels of the internal ARQ buffers storing received out-of-sequence PDUs. If e.g. in DL direction a huge number of PDUs has been sent for a specific connection within subsequent frames and the first PDU of them has been lost due to a transmission error the out-of-sequence PDUs are stored in the ARQ unit. When the PDU lost previously has been retransmitted and correctly received by the peer entity all PDUs are delivered to the Mapper unit at the RS and stored in the according connection specific buffer instance after the mapping. It is now possible that the number of PDUs delivered by the ARQ instance at once is larger than the remaining capacity of the buffer instance. To avoid PDU losses the FC unit has to monitor also the number of out-of-sequence PDUs stored at the according ARQ instance. In case the number exceeds a critical level the FC unit has to signal to its peer entity to reduce the traffic for that connection even if the threshold for the fill level of the according buffer instance has not been reached, yet.

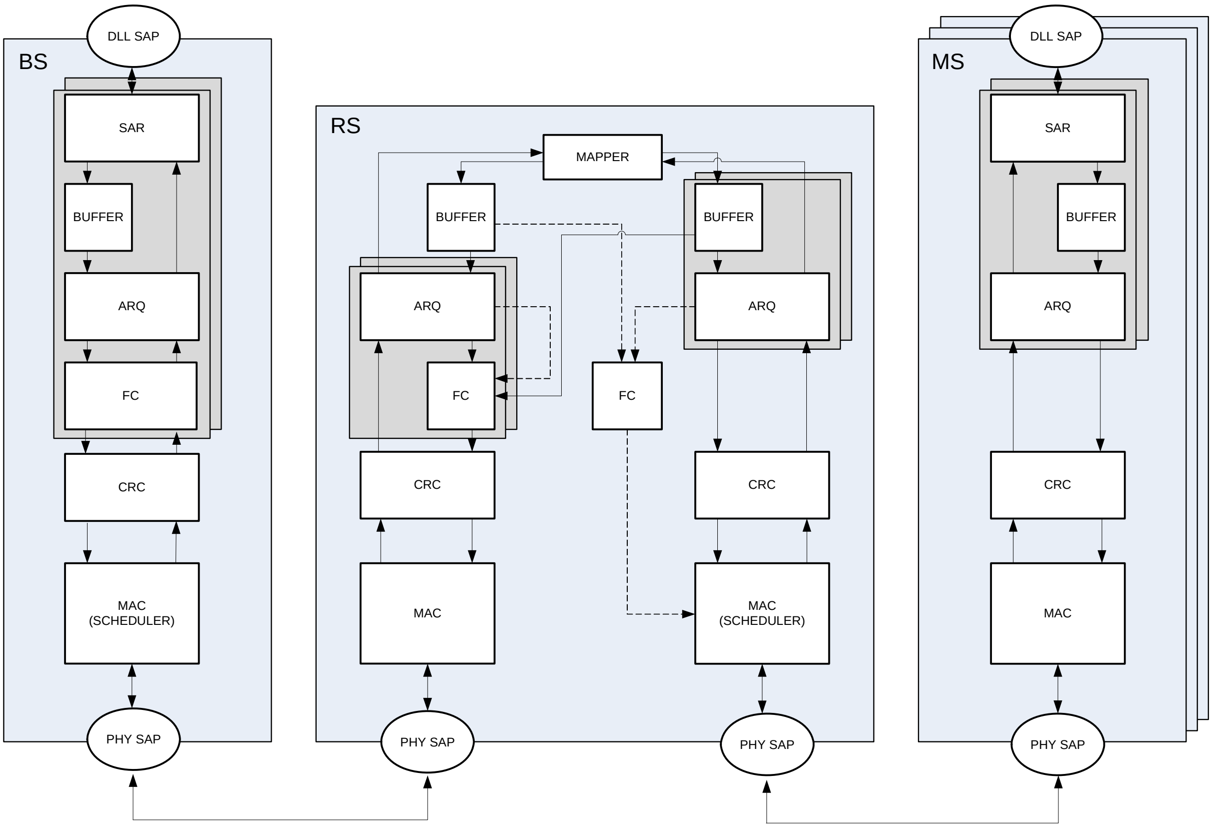


Figure 78: FC with connection based signalling with hop-by-hop ARQ

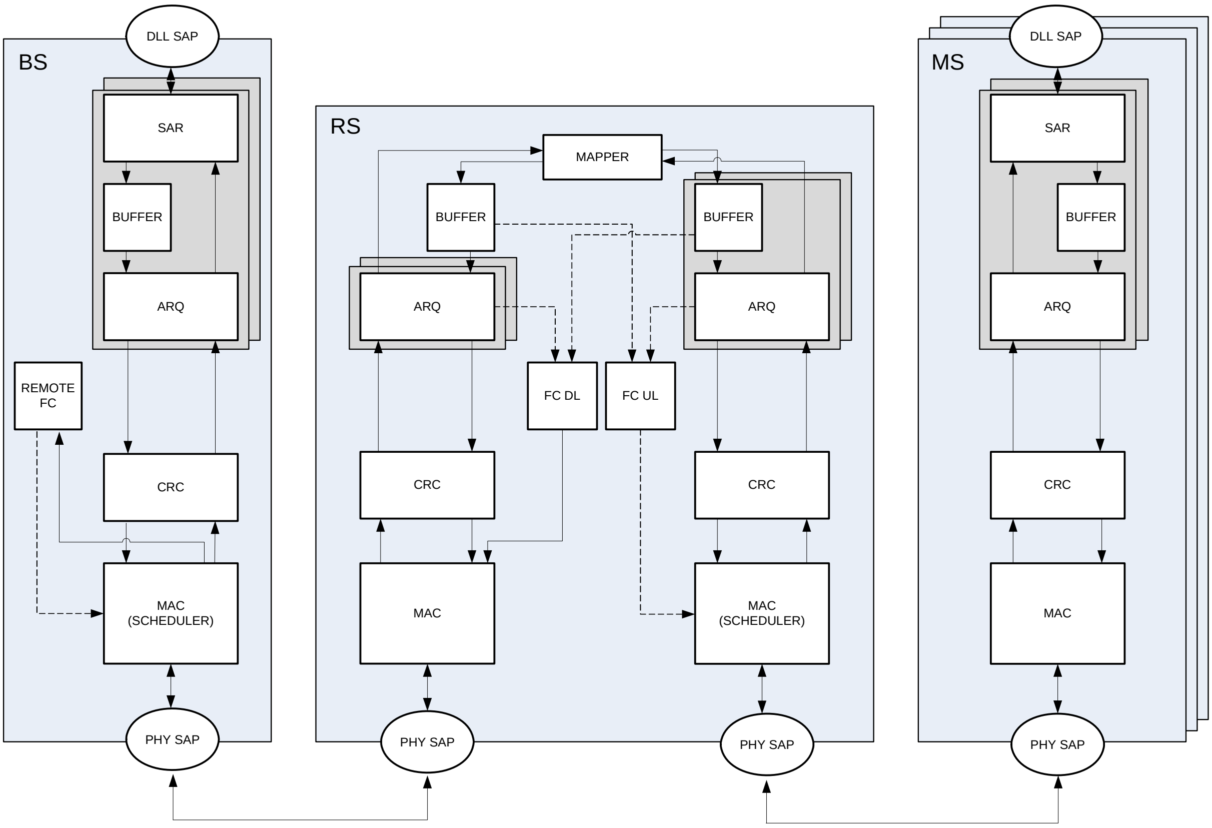


Figure 79: FC with map based signalling with hop-by-hop ARQ

3.1.2.3.2 Combination of FC and End-to-End ARQ

Alternatively, an end-to-end ARQ mechanism can be used as shown in Figure 80. An end-to-end ARQ mechanism without any flow control is sufficient to assure that no PDUs get lost in the end-to-end connection. But this method is very inefficient because it does not avoid buffer overflows in DL and UL direction and as a consequence unnecessary retransmissions of PDUs occur. The ARQ can deal with losses of PDUs due to buffer overflows because its scope includes the buffers, too. But the original task of an ARQ mechanism at DLL level to correct transmission errors on the link is shifted. In this case it initiates retransmissions of PDUs that not only have not been correctly received but also that have been lost due to a buffer overflow.

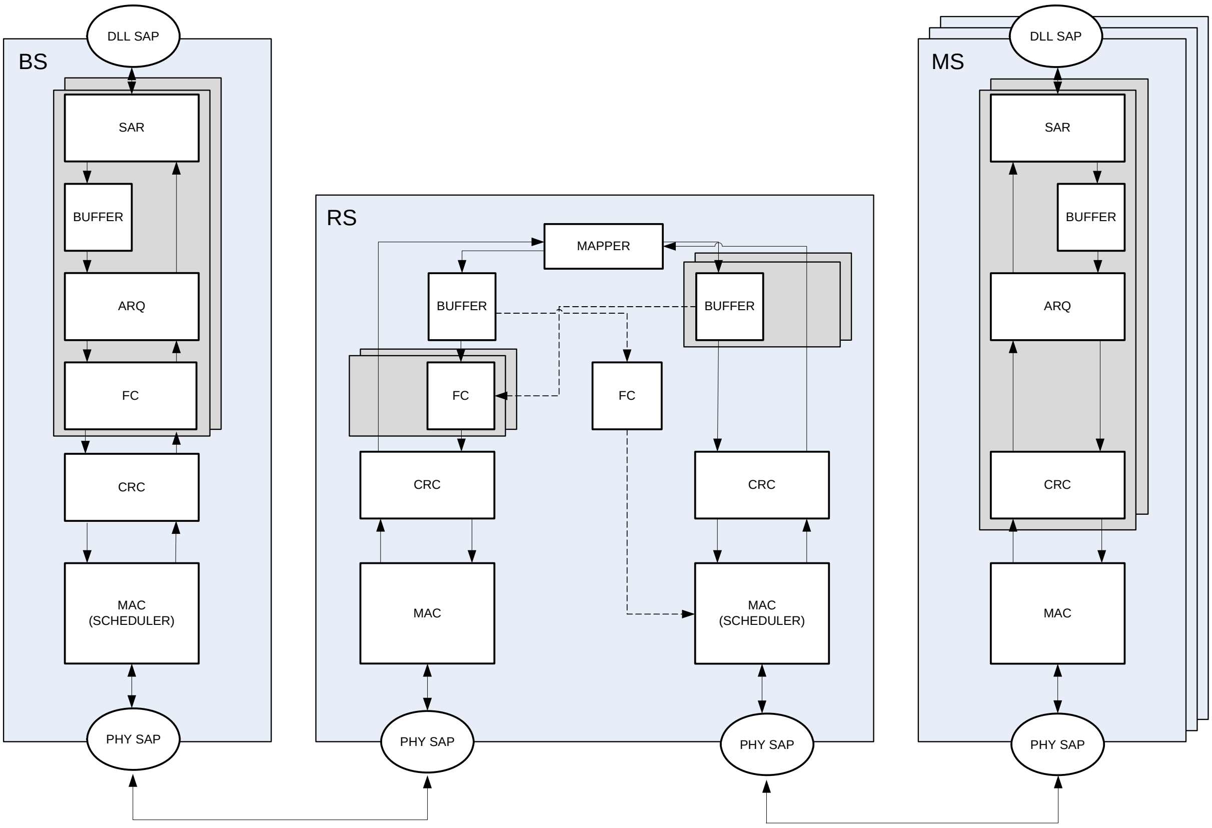


Figure 80: FC with connection based signalling with end-to-end ARQ

To increase the efficiency of connections secured by an end-to-end ARQ mechanism an FC protocol should be used. This protocol avoids unnecessary transmissions of PDUs that would lead to a buffer overflow and reduces the tasks of the ARQ mechanism to the initial one, to recognize transmission errors on the link and correct them. Again, both methods of flow control may be applied in DL direction, connection and map based signalling, as shown in Figure 80 and Figure 81.

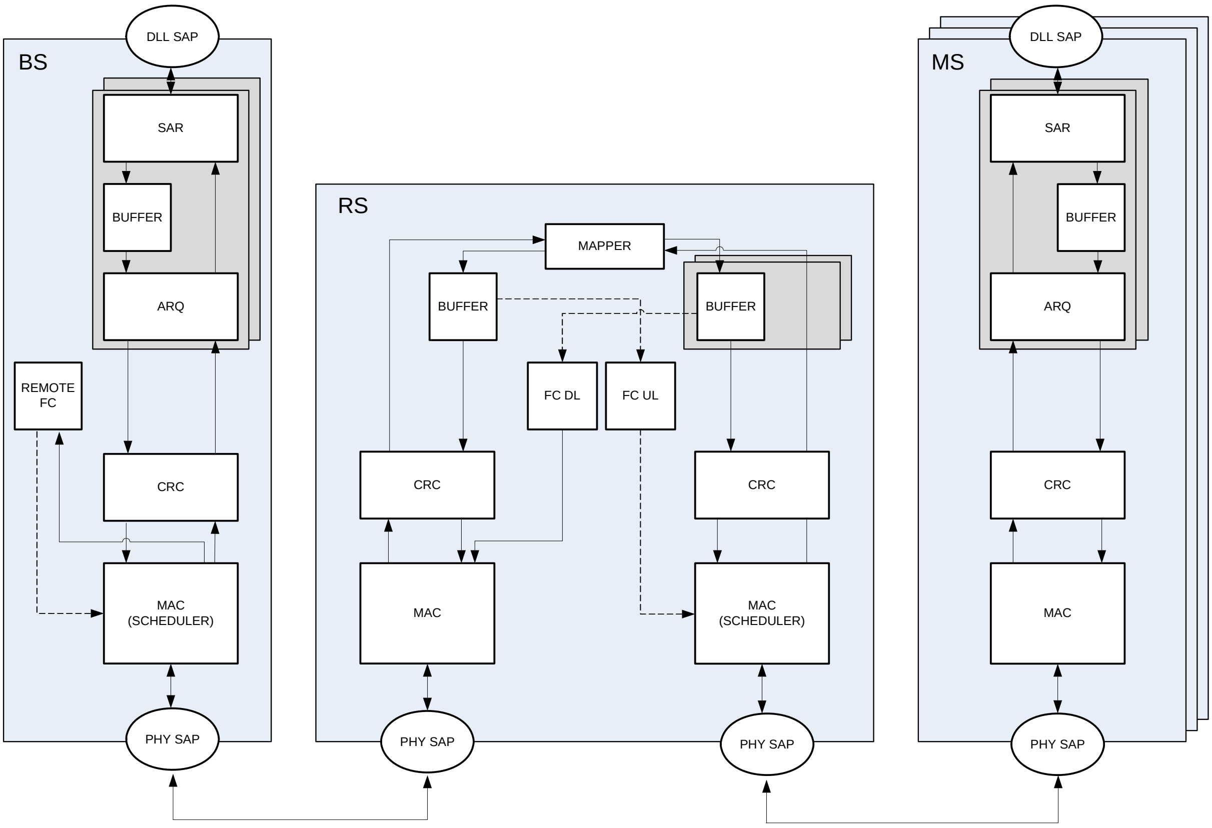


Figure 81: FC with map based signalling with end-to-end ARQ

3.1.2.4 Layered ARQ

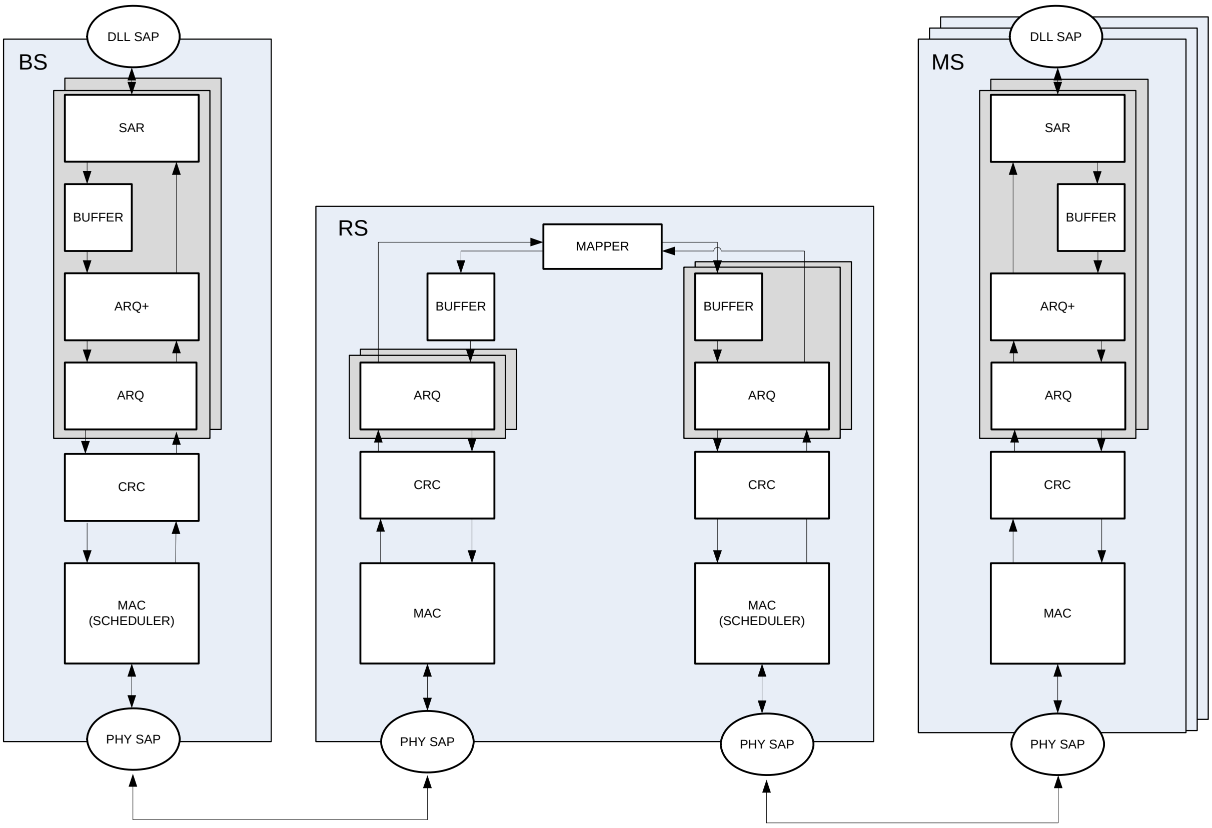


Figure 82: Combination of hop-by-hop and end-to-end ARQ

As mentioned in the previous subsection an end-to-end ARQ is sufficient to assure that no PDUs get lost. Beside the disadvantage discussed in the previous subsection it has another one: If a transmission on the first hop was successful but the transmission on the second hop not a retransmission of the erroneous PDU requires another transmission of that PDU also on the first hop. To avoid this waste of resources hop-by-hop ARQ units may be placed below the end-to-end ARQ unit as depicted in Figure 82. In this case the hop-by-hop ARQ units are responsible for correcting errors on the link and the end-to-end ARQ units are responsible for retransmissions necessary due to buffer overflows. But in this case the end-to-end ARQ is misused because it is not designed to control the traffic flow. The peer entity may start a retransmission of a PDU because an ACK has been delayed to long. Hence, instead of the end-to-end ARQ a flow control protocol is recommended.

3.1.2.5 Summary

Table 12 lists all combinations of the discussed flow control and ARQ protocols. The first and second column define the combinations, the remaining five columns briefly describe their advantages and disadvantages regarding distinct topics. The „FC signalling complexity“ depends on the average effort necessary to signal the FC information from the RS to the BS. In case of „map based“ signalling only one message per frame has to be transmitted at maximum, in case of connection flow specific signalling („In flow“) one message per connection is necessary at maximum. The „Impact of loss of FC signalling“ describes the influence of loss of signalling information on the behaviour of the FC protocol. In case of „Event-based“ signalling the loss of a single message may lead to a long lasting misbehaviour of the FC protocol when events are rare. Particularly, when using „In flow“ signalling the loss of a single message is critical. To avoid this misbehaviour a handshake mechanism can be used but this would induce additional overhead. In the column „End-to-End packet loss“ the reasons for packet loss are described. „Unnecessary retransmissions“ occur when a first hop transmission was successful but the PDU gets lost at the RS or due to transmission errors on the second hop leading to a retransmission also on the first hop. The third and fourth column are only important for DL transmissions.

Table 12: Possible ARQ/FC protocol combinations

ARQ Type	Signalling		FC signalling complexity	Impact of loss of FC signalling	End-to-End packet loss	Unnecessary retransmissions	Remarks
No ARQ	In flow	Event based	High	Critical	Transmission errors	No	
	In flow	Periodic	High	Low	Transmission errors	No	
	Map based	Event based	Low	Medium	Transmission errors	No	
	Map based	Periodic	Low	Low	Transmission errors	No	
Hop-by-Hop ARQ	No Flow Control		---	---	Buffer overflows	No	
	In flow	Event based	High	Critical	No	No	
	In flow	Periodic	High	Low	No	No	
	Map based	Event based	Low	Critical	No	No	
	Map based	Periodic	Low	Low	No	No	
End-to-End ARQ	No Flow Control		---	---	No	Yes	
	In flow	Event based	High	Critical	No	Yes	
	In flow	Periodic	High	Low	No	Yes	
	Map based	Event based	Low	Critical	No	Yes	

	Map based	Periodic	Low	Low	No	Yes	
Layered ARQ	No Flow Control		---	---	No	Yes	Synchronization of timeouts difficult

3.1.3 Evaluation

3.1.3.1 Scenario Setup

The evaluated scenario is depicted in Figure 83. The centrally located BS is surrounded by 3RSs that are placed at the border of the coverage area of the BS. The BS uses a 9-element circular dipole antenna array to allow for SDMA operation with up to four simultaneous beams. The RSs use antenna arrays as well but they perform only beam-forming instead of SDMA. Thus, the RSs are much less complex and hence less expensive.

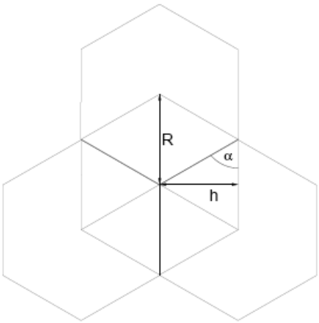


Figure 83: Scenario setup: The 3RSs per BS have equal distances to each other and are placed on the border of the coverage area of the central BS

The MAC frame setup is shown in Figure 84. The Subframe Concept introduces a reserved phase in the Uplink (UL) subframe of the 802.16 MAC frame, which is under the control of the RS. The RS takes over the responsibility to build a complete MAC frame within the reserved phase. This nested subframe contains all necessary information to interpret it as a full 802.16 MAC frame. This concept also allows the allocation of several subframes for multiple RSs of the cell. Figure 84 shows the extended MAC frame that allocates subframes for two associated RSs. Additionally the figure shows the concurrent allocation of bursts on the first and on the second hop. For a more detail description of the subframe concept see [Hoymann2006].

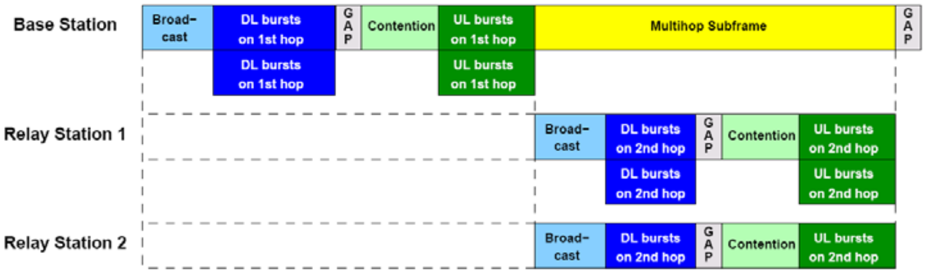


Figure 84: Setup of the Relay Enhanced Cell MAC frame

Further simulation parameters are shown in Table 13.

Table 13: Simulation parameters

Number of MSs per BS (1-hop connections)	12
Number of MSs per RS (2-hop connections)	8
Path loss model	Free space
Tx frequency	5GHz
Frame length	10ms
Packet size	3000bit (fix)
Packet IAT distribution	Exponential
Offered data rate per Relay Enhanced Cell	10kb…30Mb

3.1.3.2 Simulation Results

Figure 85 shows the carried DL throughput over the offered DL traffic without any ARQ or flow control mechanism for different subframe ratios. The subframe ratio denotes the ratio of the length of the relay subframe to the length of the whole frame. For the investigated scenario a subframe ratio of 0.25 (green graph) results in the highest cell throughput. For smaller or larger subframe ratios the cell capacity is lower because the capacities of the first- and second-hop link are imbalanced. If not stated otherwise in the following investigations the optimal subframe ratio 0.25 is used.

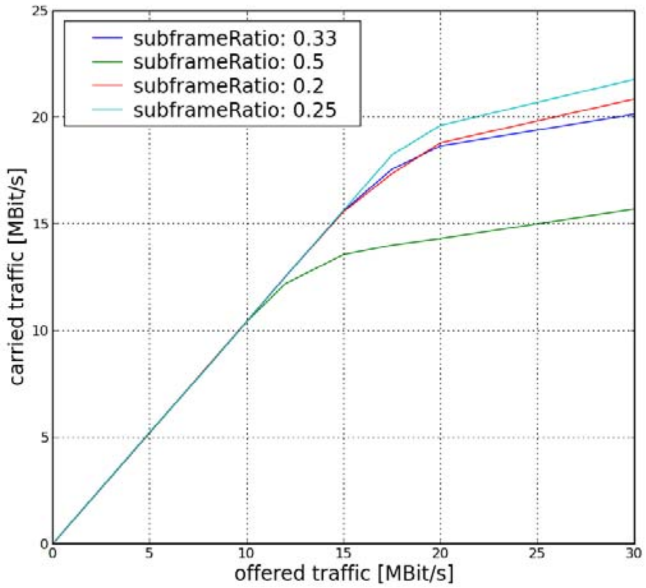


Figure 85: Aggregated carried DL traffic over offered traffic without ARQ and flow control

In Figure 86 the green coloured graph again represents the case where no flow control and no ARQ mechanism is used. For that case for an offered system load of 17.5Mb per second nearly all traffic can be carried and only few packets get dropped due to transmission errors. If a setup with an end-to-end ARQ mechanism, illustrated in Figure 80, is used as it is the case for the cyan graph the saturation point is already reached for an offered load of 15Mb per second. The used end-to-end Go-Back-N ARQ mechanism requires the retransmission of packets. Hence, the first and second hop links are more loaded compared to the case where no ARQ mechanism is used at all and the system runs in an overload condition earlier. Besides packets that are lost due to transmission errors in this setup packets are also lost due to buffer overflows at the second hop DL buffers in the RSs. This problem is shown in Figure 87. The cyan graph represents the buffer loss ratio of the second hop DL buffers in the RSs. For a load of 17.5Mb per second 11% of all packets received at the RSs are dropped and have to be retransmitted by the ARQ.

The red graph in Figure 86 shows the carried system load for the case that beside the ARQ mechanism additionally ideal flow control is applied. Ideal flow control means that no signalling information is transmitted from the RSs to the BS and there is no delay in controlling the packet flow. For this setup the carried system load is up to 15% higher than without flow control. The gain results from the decreased packet loss ratios at the DL buffers at the RSs. Actually, no packets get lost for ideal flow control as can be seen in Figure 87 (blue graph). The proposed in-flow and map-based signalling mechanisms are expected to provide a performance that is better than for the setup without flow control and that is worse compared to the setup where ideal flow control is applied.

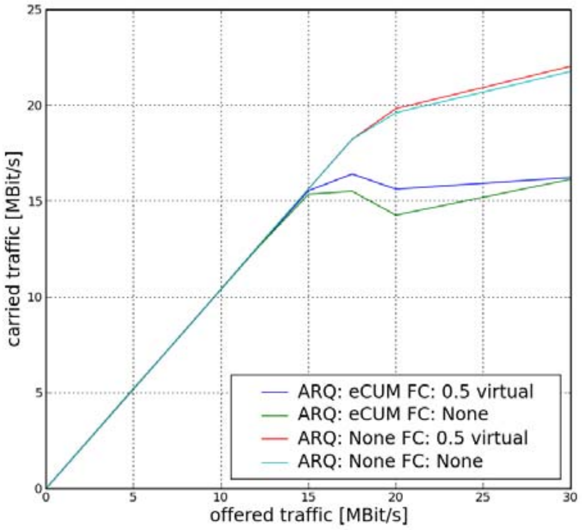


Figure 86: Aggregated carried DL traffic over offered traffic

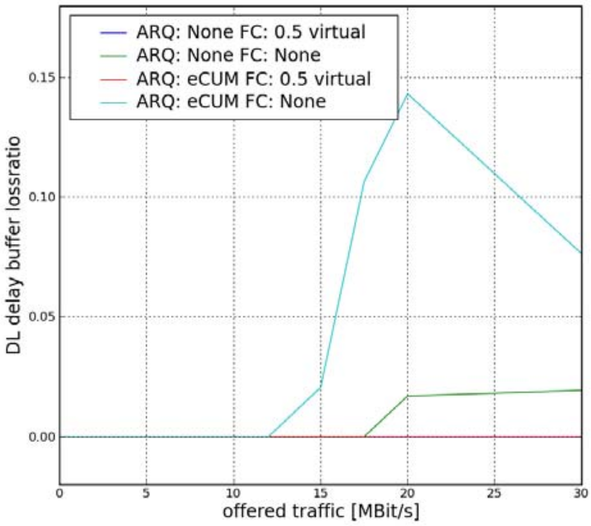


Figure 87: Packet loss ratio at the DL RS buffer

In Figure 88 the average DL throughput per MS is plotted over the offered DL system load differentiated for one- (MS) and two-hop (RMS) stations. The blue and red graph show the carried traffic for the case that no flow control and ARQ is used. Again, the whole offered traffic can be carried even for an offered load of 17.5Mb per second. But in case an ARQ mechanism with flow control is used the carried traffic differs for both types of stations. The throughput for one-hop MSs is higher than for two-hop RMSs because the probability that a packet gets lost during a single transmission is smaller than for two consecutive transmissions. Thus, one-hop MSs are preferred over two-hop RMSs. If all types of stations shall get the same data rate the priority of two-hop RMSs has to be higher than the priority for one-hop MSs. This issue is currently still under investigation.

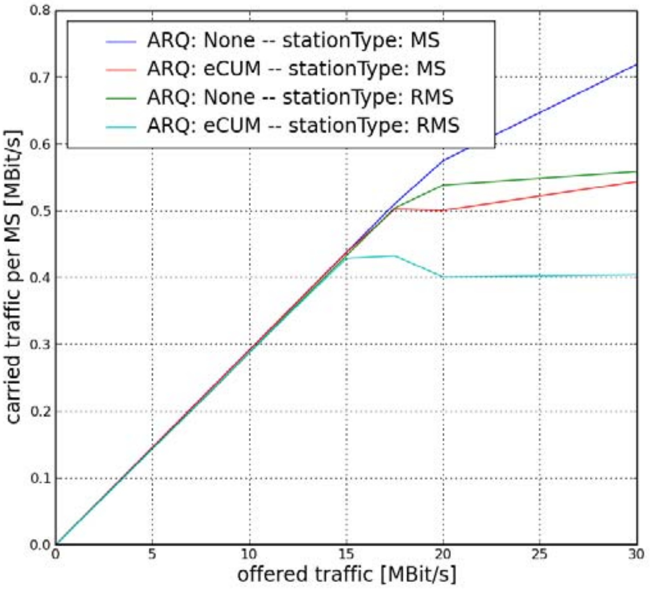


Figure 88: Carried DL traffic per MS over offered traffic

In Figure 89 the Complementary Cumulative Density Function (CCDF) of the packet delay is plotted for an offered DL system load of 17.5Mb per second differentiated for one- and two-hop stations. The red graph shows the delay for two-hop RMSs that use flow control, the cyan graph represents the case without flow control. The transmission delay from 95% of all packets is below 2 seconds with flow control but below 1 second without flow control. Thus, the increased throughput when using flow control is reached at the expense of a higher delay. The delay of the one-hop MSs plotted as green and blue graphs is negligible as there is no relay buffer that can overflow and the Packet Error Rate (PER) is very low.

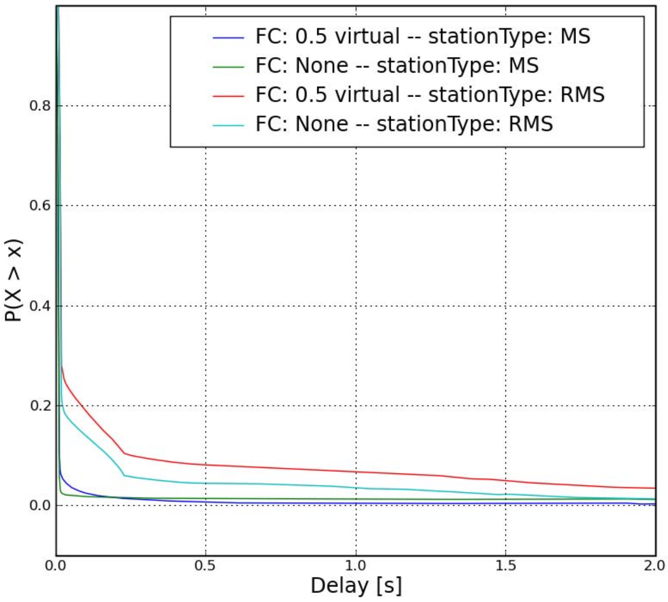


Figure 89: CCDF of the packet delay for one- and two-hop MSs

The CDFs of the windowed fill levels of the DL buffers at the RS are plotted in Figure 90 for an offered load of 17.5Mb per second. When no flow control is used (red graph) 15% of the simulation time the buffer overflows and about 85% of the simulation time the fill level is below 0.1. The green graph represents the case when ideal flow control is used. The packet flow is interrupted when the buffer fill level reaches 0.5. As can be seen the buffer does not overflow at any time during the simulation, but fill levels of about 0.9 may rarely occur. The blue graph shows the case where the above introduced in-flow signalling of flow control information is used. The characteristic of the graph is very similar to the characteristic of the red one. This means that the reporting period of about each seventh frame chosen for the in-flow signalling is too large to reach any gain through flow control. Hence, smaller reporting periods are currently under investigation.

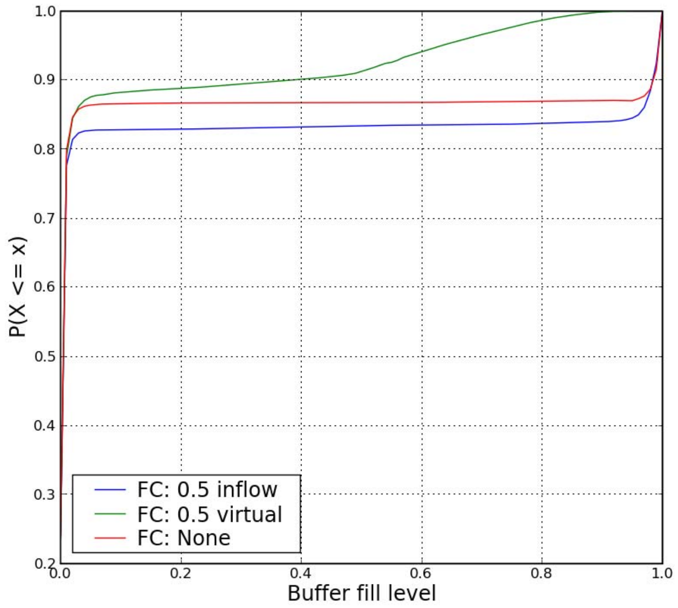


Figure 90: CDF of the buffer fill levels at the RS for DL direction

3.1.3.3 Conclusions

The single-cell scenario shows that for the optimal subframe ratio 0.25 flow control brings benefits mainly in overload situations. By avoiding buffer overflows in the DL relay buffer through flow control the carried throughput can be increased up to 10%. The results for the ideal signalling of flow control information show that the increased throughput is reached at the expense of an increased delay. Furthermore, the reporting period of flow control information is a crucial parameter. The investigated reporting period of about 70ms is far too large to gain benefits through flow control. Hence, shorter reporting periods should be investigated.

3.2 Spectrum Access by Mutual Observation

If cells are coordinated by mutual observation, transmission opportunities can be identified by BS or SSs. Here exemplarily for the downlink, we propose to let the SSs acquire the needed information and let them send the spectrum usage pattern to the BS. This approach allows accounting for individual SINR situation of each SS in downlink and thereby for more efficient link adaptation.

Figure 91 shows an example receive power pattern, perceived by a single SS. The power peak of the frame header is depicted as well as a DL transmission to the observing SS. In a second step the SS transmits the measured power pattern to the BS.

The BS processes the pattern by subtracting its own transmissions pattern considering all transmissions to SSs of its cell. Figure 92 depicts the transmit pattern of the BS, indicating the frame header and three DL transmissions. Now the BS can generate a filtered power pattern for each SS, shown in Figure 93, by combining the patterns of Figure 91 and Figure 92. With the filtered power pattern, the BS is able to identify transmission opportunities and exploit them by allocating new downlink transmissions to these unused resources.

The required signalling overhead (for sending the interference level perceived at the SS to the BS) depends on size of the transmission opportunities and the quantization of the measurement. Table 14 presents the resulting overhead rates of different sampling frequencies (from 0.1 to 7.2 kHz) and types of quantization (from 1 to 4 bit). For example if a SS generates one sample per 10 OFDM symbols (i.e. 7.2 kHz sampling frequency with $T_{symbol} = 13.89x10^{-6}$s) and uses a 4 bit quantization (allowing 16 different interference levels), it produces a signalling traffic of 28.8 kbit/s. This resource consumption can be further reduced by scanning on demand and using lower quantization. Only one bit per sample is required if a threshold is used at the SS for deciding whether a transmission opportunity is to be used or not.

For a signalling traffic of 28.8 kbit/s the resulting symbol occupation is given in a Table 15. This Table bases on the switching points of the MCS in a free space propagation scenario with uniformly distributed SS in a cell [Figure 94]. A SS at the cell edge using BPSK 1/2 occupies in average three symbols per frame whereas a SS close to the BS using 64 QAM 3/4) occupies in average one symbol every third frame.

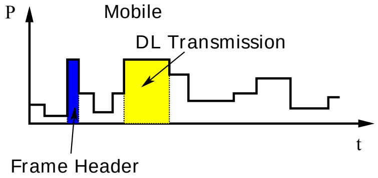


Figure 91: Perceived receive power at the SS

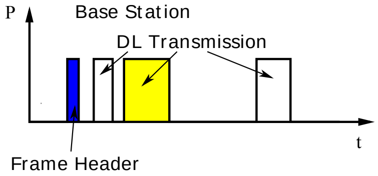


Figure 92: Transmit pattern of the BS

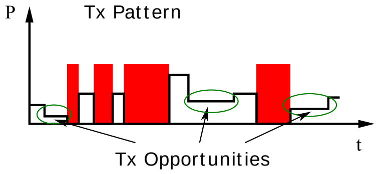


Figure 93: Filtered power pattern of the SS

Table 14: Overhead rate of approach "observing SS"

	Quantization [bit]			
Sampling Frequency	1	2	3	4
100	100	200	300	400
200	200	400	600	800
400	400	800	1200	1600
800	800	1600	2400	3200
1600	1600	3200	4800	6400
3200	3200	6400	9600	12800
7200	7200	14400	21600	28800

Table 15: Resource consumption for an overhead rate of 28.8 kbit/s; Mean: 1.99 symbols per frame per user

Modulation and Coding Scheme	User percentage	Bits per symbol	Symbols per frame at 28.8 kbit/s
BPSK 1/2	39.4	96	3
QPSK 1/2	20.56	192	1.5
QPSK 3/4	27.95	288	1
16 QAM 1/2	4.1	384	0.75
16 QAM 3/4	5.15	576	0.5
64 QAM 2/3	0.92	768	0.375
64 QAM 3/4	1.92	864	0.33

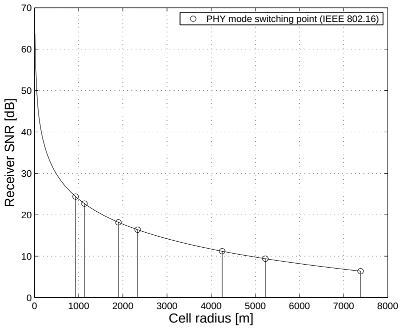


Figure 94: IEEE 802.16 OFDM switching points with free-space, 20 MHz bandwidth, single cell

4 CONCLUSIONS

In this deliverable two different aspects for improvement of the spectral efficiency of IEEE 802.16m compliant systems are addressed – link-level and system-level reconfiguration. The investigations on link-level reconfiguration focus on the reduction of ARQ signaling overhead. Analytical results show that the dynamic adaptation of the ARQ segment size depending on the channel quality leads to minimal cell capacity gains, only. But the control and signaling of dynamic segmentation is very complex and out of proportion to the possible benefits. Hence, this issue has not been further investigated.

An analysis of the overhead reduction through different new acknowledgement schemes is done for scenarios with and without RSs. Varying ARQ segment size, PDU Size and amount of user's data per frame are considered in the evaluations. The best performance (from management overhead reduction point of view) is achieved by proposal III, a combination of sending only negative ACKs and BSNs of blocks with errors. The ratio of overhead reduction heavily depends on the combination of all ARQ related parameters and also on the BLER level. When considering RSs, the efficiency of proposal III is decreasing with higher number of hops. For some specific combinations of ARQ parameters, the proposal III can even increase the overhead for high levels of BLER. However, for all levels of BLER it is possible to find sets of combinations of parameters resulting into significant reduction of overhead. The proposed solution is designed with respect to not increase the ARQ delay.

Furthermore, the ARQ proposal III is evaluated together with HARQ technique. Four combinations of ARQ and HARQ are considered: conventional ARQ & HARQ with and without interaction between both; ARQ proposal III & HARQ with and without interaction. The evaluation is performed over the set of ARQ and HARQ parameters. While no interaction is enabled, the proposal III leads always to overhead reduction. Moreover, the results show a positively considerable impact of the interaction between ARQ (conventional as well as proposal III) and HARQ on overhead reduction. The positive impact of proposal III, if interaction is enabled, is noticeable for some special configurations of ARQ parameters (high PDU Size and low ARQ segment size). The impact of HARQ type and maximum number of HARQ retransmissions on the overall ARQ & HARQ overhead reduction by ARQ proposal III is also noticeable for small ARQ segment sizes and large PDU sizes.

The investigations on system-level reconfiguration mainly focus on flow control in relay enhanced cells. A large number of combinations of flow control and ARQ mechanisms to efficiently provide packet-loss free connections is listed and their advantages and disadvantages are described. Single-cell simulation results show that even for an optimal subframe ratio flow control leads to additional cell capacity gains of up to 10%, at least in high load conditions. The cell capacity gains are even larger if the subframe ratio is not chosen optimally. Furthermore, the results for the ideal signalling of flow control information show that the increased throughput is reached at the expense of an increased delay. The reporting period of flow control information is a crucial parameter that should not be chosen to large.

A further topic of system-level reconfiguration is the efficient signalling of resource usage patterns. The signalling mechanism proposed in this deliverable allows for spectrum access by mutual observation. Analytical results show that the signalling overhead is small.