Throughput Parameter Optimization of Adaptive ARQ/HARQ Scheme

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Abstract: In this paper, we construct an adaptive ARQ/HARQ scheme using RS code for error correction and CRC code for error detection (when working in pure ARQ). Scheme performance parameter is defined and investigated to find optimal threshold values. Simulations are performed in LMS channel.

Keywords: adaptive ARQ/HARQ, Reed-Solomon, land mobile satellite, rayleigh fading, simulation, parameter optimization.

1. Introduction

When transmitting through channels with errors, the most common solution is to implement standard automatic repeat request (ARQ) strategies (considering feedback channel is available), such as Stop and Wait (SW), Go-Back-N (GBN), or Selective Repeat (SR) [1]. Also several modifications to classic ARQs have been introduced to increase performance and reduce unnecessary repetition, e.g. multicopy GBN [2], [3] or delay modifications [4]. These algorithms however are effective only in channels with low error rate because any single errored bit causes whole packet to be discarded and re-sent.

Hybrid ARQ methods (HARQ) extend the communication ability of ARQ in considerably lower levels of signal to noise ratio (SNR) employing forward error correction codes (FEC). There are three types of HARQ schemes (HARQ type I, II and III) [5]. HARQ type I has less redundancy and much simpler physical layer than the other two because it does not need additional buffering on the transmitter side [6]. Types II and III operate using adaptive incremental redundancy (AIR) that, in case of error, does not always require to re-send the whole packet. Instead, it sends additional redundant bits, that are merged with errored packet, to increase FEC error correction capability [5].

Due to code redundancy, the main disadvantage of all HARQ schemes is the throughput in less noisy channel, which is significantly lower than the throughput of pure ARQ. To make it more powerful, we have to consider the adaptive scheme which would switch, according to the state of communication channel, between classic ARQ and other scheme that is less prone to errors. Popular adaptive ARQ implementations are [7] and [8]. In [9], the adaptive scheme employs convolutional code with Viterbi based decoding.

2. New Adaptive Scheme

The process of developing adaptive ARQ scheme has two main stages:

1. Choosing the type of transfer scheme used in high error state.
2. Designing the adaptation algorithm that manages switching between pure ARQ and the other scheme.

2.1 HARQ Scheme Used

In our approach, HARQ type-I with RS (Reed-Solomon) code is chosen as FEC. The reason for using RS is that in common environments channel errors occur in bursts and often are not mutually independent [10]. Under such circumstances, the RS code is much more efficient because it can handle error bursts very well [11].
Main structure of RS codes is shown in Figure 1 [12].

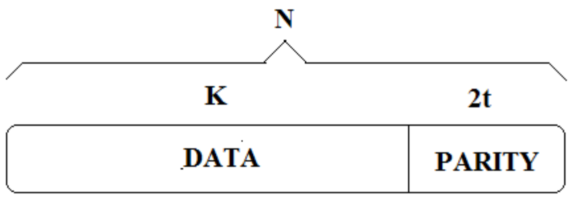

Figure 1. Code word of RS code

RS code [*N*, *K*, *t*]
N – Length of code word (in RS symbols)
K – Count of information symbols (data)
t – Count of repairable symbols (*2t* = redundancy)

$$t = \frac{(N-K)}{2} \qquad (1)$$

Code word is created by generating polynomial:

$$g(x) = (x+\alpha^{i}) \cdot (x+\alpha^{i+1}) \cdot \ldots \cdot (x+\alpha^{i+2t-1}) \qquad (2)$$

for $i = 0,1,\ldots,2t-1$

2.2 Considered ARQ Strategies

Our main focus is on GBN and SR transfer modes. The main advantage of GBN is a good throughput at low implementation complexity since it does not require buffering on the receiver side. SR mode, on the other hand, has the best throughput, but at the cost of a higher complexity. We also analyze the SW mode, but only marginally, as with increasing delay its throughput quickly deteriorates beyond usable values (shown in Figure 15). Anyway, our presented methodology for optimizing an adaptive throughput is independent of a transfer mode.

2.3 The Adaptation Algorithm

The design of the adaptation algorithm is a very important part of the whole scheme as the final throughput is dependent on its performance.

We consider the forward channel to have two states; L state (low error rate) and H state (high error rate), as shown in Figure 2 [8].

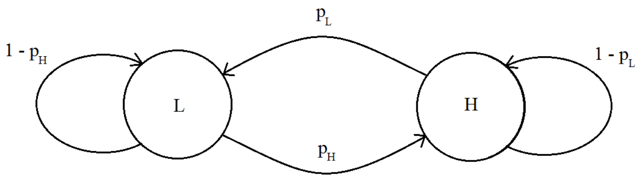

Figure 2. Channel model with 2 states: low error and high error state with probabilities of changing or not changing the state

From this Gilbert model [10] (Figure 2), based on assumptions made by Sastry in [7] and modified by Yao in [8], the switching scheme can be derived (Figure 3). Big advantage of this model is that it does not require the knowledge of instantaneous packet error probability [8]. This channel state model is used to describe the way of switching between transfer methods.
In [13], we have modified the original Yao's model to work with pure ARQ and HARQ type I transfer mode using RS coding (Figure 3).

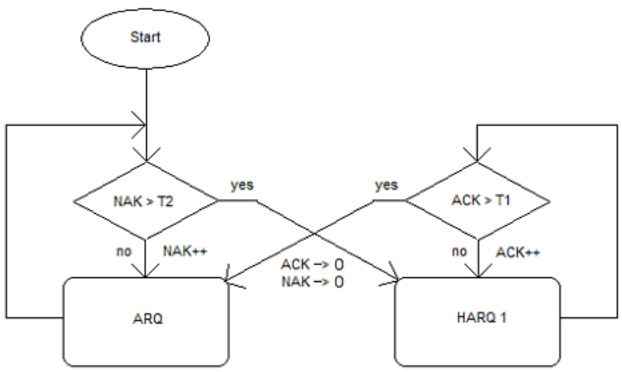

Figure 3. Proposed Adaptive ARQ/HARQ Scheme

Based on our work in [13], we continued further by introducing an objective performance criterion, using which we are able to investigate the throughput performance of proposed scheme and find optimal parameter settings for every channel conditions. Furthermore, it is possible to automatize the search, so we are able to determine the best parameter values for any transmission setup. We also consider the other ARQ schemes and by attaching the appropriate error detection (CRC) code to the packets in pure ARQ mode, we create robust detection-correction system.

2.4 Scheme throughput

Corresponding to the two channel states, there are two operation modes in the proposed scheme.
In channel state *L*, the transmitter follows the pure GBN or pure ISR ARQ and the throughput can be expressed as [14]:

$$\eta_{B-GBN} = \frac{1-P_e}{1+S\cdot P_e} \tag{3}$$

$$\eta_{B-ISR} = 1-P_e \tag{4}$$

where P_e is the block error probability which can be expressed as:

$$P_e = 1-(1-P_b)^n \tag{5}$$

where P_b is a bit error probability in BSC, n is the block length and S is the delay expressed in data blocks.
In channel state *H*, the transmitter works in HARQ transmission mode. It encodes the data before transmission using RS [*N*, *K*, *t*] code. As stated in Figure 1, the RS code used is able to repair *t* symbol errors. Its code word length is *N* symbols and its information word length is *K* symbols with code rate *K/N*. Its throughput can be expressed as [14]:

$$\eta_{H-GBN} = \frac{1-P_{He}}{1+S\cdot P_{He}} \tag{6}$$

$$\eta_{H-ISR} = 1-P_{He} \tag{7}$$

where P_{He} is block error probability for channel state H.

2.5 Parameters Description

In Figure 3, you can see two parameters – threshold *T1* and *T2*. These parameters are used as a limit for positive and negative acknowledgements respectively. When the amount of consecutive NAKs in low error state overreaches the threshold *T2*, the transmission mode is switched from ARQ mode to HARQ. In high error state, when the amount of consecutive ACKs overreaches the threshold *T1*, the transmission is switched back from HARQ to ARQ. The ACK/NAK counters are reset to zero after every mode switch.

3. Construction of the Simulator

After specifying all parameters for transmission and schemes, we are ready to build a simulator to find optimal threshold parameters.
We have constructed a simulator that can work with all common ARQ strategies and its parameters are described below.

3.1 Modes of Operation

The simulator has two modes of operation:

- No-RS
- Full-RS

When Full-RS mode is requested, FEC recovery data from RS code is appended to the end of the packet, extending it to the length of *N*. In No-RS mode, the data packet of length *K+CRC* is sent, where *CRC* value means error detection code length. In our simulations, we use 32-bit CRC code, which is the same as used in ethernet frames that contain comparable number of bits [15].
Similar overall approach of changing packet length is used also in wireless broadcast [16].

3.2 Delay

Round-trip delay is always considered in the simulation. At the start of the simulation, it is expressed in multiples of data length (*K*), because this is the only value that is present in all modes. Delay in case of ARQ/HARQ scheme cannot be expressed exactly in number of slots, because the packet length changes over time (as RS gets involved). The delay is, therefore, always evaluated to be of the same length (in bits); no matter the current transfer mode (all simulation results presented in this paper have delay set to 5 times *K*).

3.3 Channel Model

The underlying channel model used is Land Mobile Satellite (LMS) [17], [18]. Statistical properties of the LMS channel depend on attributes of surrounding environment. According to this, we have implemented three channel modes:

3.3.1 Urban Environment

In urban areas transmitter and receiver are surrounded by many obstacles (e.g. buildings) that attenuate line-of-sight (LOS) transmission waves. Therefore, signal reception undergoes fading with Rayleigh distribution [19] that is expressed as

$$p(x) = \frac{x}{\sigma^2} e^{\left(-\frac{x^2}{2\sigma^2}\right)} \quad (8)$$

for $x > 0$, where σ is distribution of additive white Gaussian (AWGN) noise.

3.3.2 Rural and Suburban Environment

Attenuation of LOS wave in this environment is less significant and signal propagation undergoes log-normal distribution [18]:

$$f(x) = \frac{e^{-((\ln x)^2/2\sigma^2)}}{x\sigma\sqrt{2\pi}} \quad (9)$$

for $x \geq 0$; $\sigma > 0$

3.3.3 Open Environment

With no obstacles in signal path, the received signal is given by sum [18]:

$$r(t) = l(t) + m(t) + n(t) \quad (10)$$

where *l(t)* is LOS wave, *m(t)* is scattered wave and *n(t)* is AWGN noise.

3.4 Simulator Description

The simulator itself is written in C++ and consists of several parts. The first part creates the underlying channel model that generates a bit error sequence for every specified SNR value from defined range. Above that, there is a packet processor that takes the generated bits and continually splits them into packets. The packets are then evaluated for bit errors and, if needed, the retransmission is requested (the delay of ACK/NAK packet is also considered). The decision about transfer mode change is made here, too.
After the simulation, gathered information is processed into graphs and the output is done into matlab file format to allow further data analysis.

4. Throughput analysis

We evaluate the throughput performance of the proposed ARQ scheme under the following assumptions:

1. The feedback channel of the system is error-free.
   As described in [20], feedback errors degrade the throughput of the scheme, but their effect on the parameter optimization turns out to be almost negligible.
2. Errors in consecutive packets occur independently.
   We assume that mutually independent bit errors are distributed according to selected channel model (section 3.3). RS codes achieve the best performance when repairing error bursts [11]. Therefore, independent errors are considered the worst-case scenario for the throughput performance. (It is also possible to simulate the real channel with error bursts and packet losses [21], but for our purpose it does not affect the main outcome of this paper.)
3. Channel errors are always detected.
   We assume that error detection code is robust enough to detect all channel errors in both ARQ and HARQ (because RS code is error detection code too).

All simulations are performed in defined range of SNR values. The results are expressed as the throughput in dependence of SNR or BER. In Figure 4 and Figure 5, you can see output from several simulations with parameters specified in Table 1.

Table 1. Simulation parameters

Channel model	Rural
Simulated SNR range	3 dB - 18 dB
RS code	[511,255,128]
Delay	5*K = 1275 symbols
ARQ mode	GBN

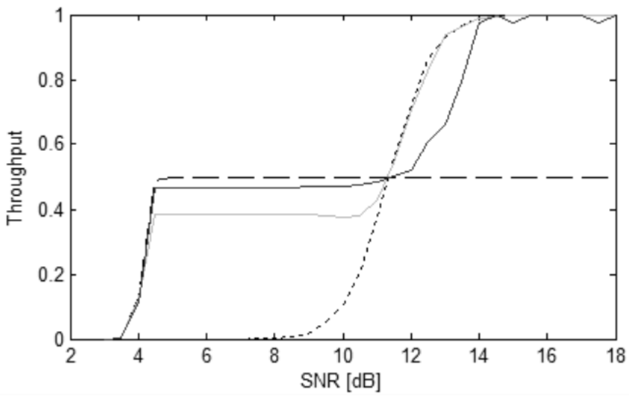

Figure 4. Throughput in dependence of SNR of adaptive ARQ/HARQ method; Lines: **solid black** - adaptive with ACK=45, NAK=3; **solid grey** - adaptive with ACK=20, NAK=2; **dashed** - ideal HARQ; **dotted** - ideal ARQ

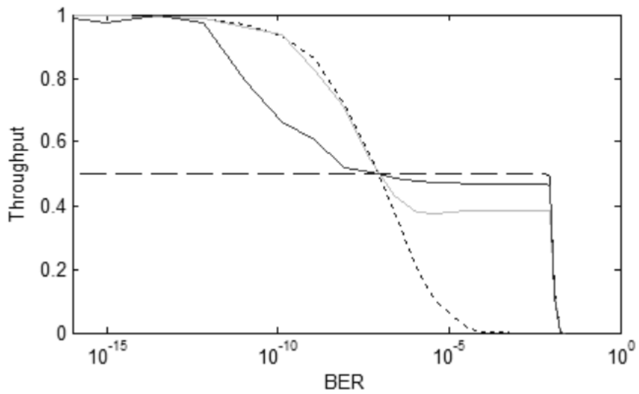

Figure 5. Throughput in dependence of BER. Line descriptions are the same as in Figure 4

In previous figures, the ideal ARQ (dotted) and the ideal HARQ (dashed) are outlined. These were obtained by two independent simulations with no switching at all.

You can easily notice two sections in the graph (divided at approx. 11 dB). In the part of lower SNR values HARQ method is dominant, whereas at high SNR pure ARQ takes control.

The throughput in all graphs is normalized to 1, where 1 means full communication throughput without any bit errors but also without any error detection code. In real applications, error detection code has to be always present; otherwise the scheme cannot detect errors and subsequently cannot switch to FEC.

You can also see that the tuning of scheme threshold parameters is essential for obtaining the best performance.

5. Optimization of the Performance Parameter

To be able to numerically express performance differences between various parameter settings and consequently evaluate performance, it is necessary to establish objective comparative criterion.

5.1 Ideal ARQ/HARQ Graph

After obtaining ideal curves for both modes, we can merge them to construct ideal throughput of adaptive ARQ/HARQ. Merging is done by taking higher throughput value from both of them in every generated SNR value. Mathematically described:

$$\eta_{IDEAL_{SNR}} = \max(\eta_{ARQ_{SNR}}, \eta_{HARQ_{SNR}}) \qquad (11)$$

where η is the throughput for respective scheme at given SNR.

The graph for ideal ARQ/HARQ performance is shown in Figure 6. In the next figures we will show these curves independently, as it allows to see more performance information.

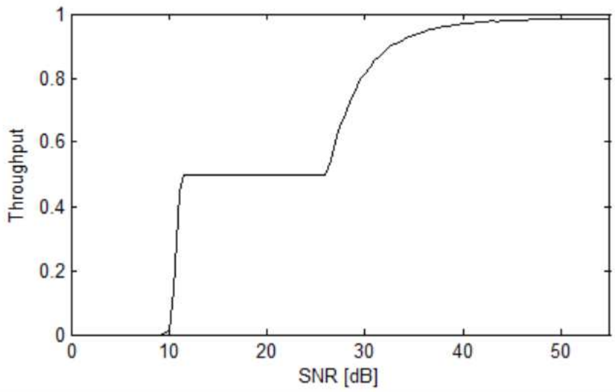

Figure 6. Ideal throughput of adaptive ARQ/HARQ method (urban environment, RS[511,255])

To produce ideal ARQ/HARQ curve in Figure 6, urban LMS channel was used. Notice that the channel change causes mostly only a horizontal shift of values in the graph.

5.2 Performance Parameter Definition

From now on, we have ideal curve that can be used to compare simulated results against the best possible values. This difference is expressed as

$$\eta_{DIFF} = \eta_{IDEAL} - \eta_{SIMULATED} \qquad (12)$$

Output of such comparison can be seen on Figure 7.

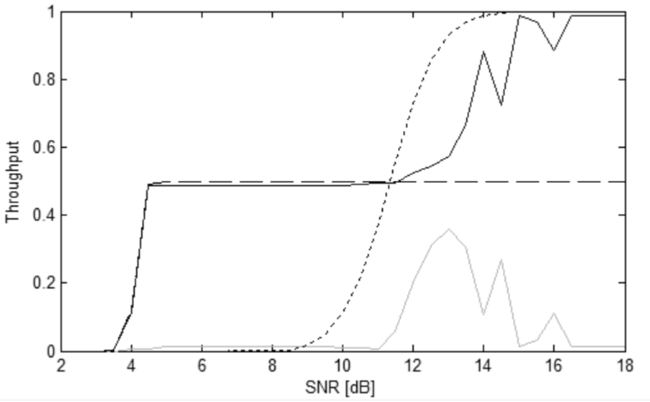

Figure 7. Throughput in dependence of SNR of proposed scheme; Lines: **solid black** - adaptive scheme, GBN, rural env, ACK=45, NAK=4; **solid grey** - difference between simulated adaptive scheme and ideal ARQ/HARQ throughput; **dashed** - ideal HARQ; **dotted** - ideal ARQ

Solid grey line represents the difference between simulated (solid black line) and ideal throughput.
Finally, from this difference, single performance parameter can be derived. The parameter is computed as mean square error (MSE), defined as

$$P = \frac{1}{M}\sum_{SNR}(\eta_{IDEAL_{SNR}} - \eta_{SIMULATED_{SNR}})^2 \qquad (13)$$

where P is our performance parameter and M is number of simulated SNR values.

5.3 Performance Parameter Optimization

From Figure 7 and (13) is apparent that the lower is the values of parameter P, the higher is overall scheme throughput.
Having single parameter describing performance of scheme threshold setup, it enables us to continually iterate whole parameter range, constructing graph of overall performance for all parameter setups. Example of such graph is in Figure 8.

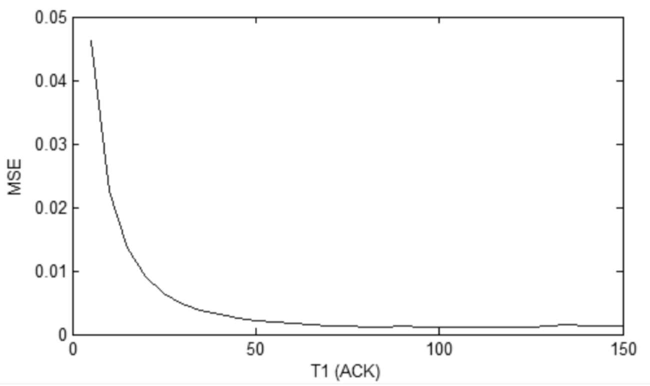

Figure 8. Scheme performance evaluation

In Figure 8, you can see performance parameter values in dependence of scheme parameter *T1*. With closer look at the same graph in Figure 9, you can see better that optimal parameter has been found.

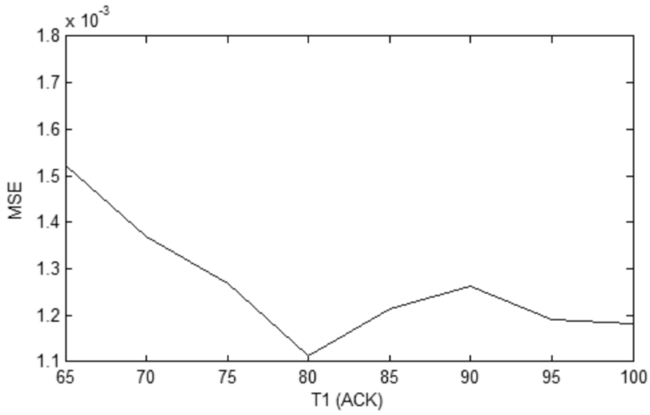

Figure 9. Scheme performance evaluation - zoomed

Using this technique, we can easily find the best parameter for selected environment. For this case, the optimal value of parameter *T1* is 80. Resulting throughput is shown in Fig. 10.

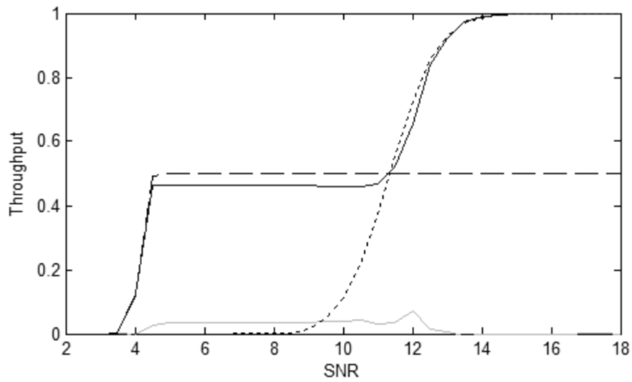

Figure 10. Scheme throughput with optimized parameter *T1*; RS [511, 255], **solid black** - ACK=80, NAK=2; **solid grey** - throughput difference from adaptive scheme and ideal ARQ/HARQ; **dashed** - ideal HARQ; **dotted** - ideal ARQ

5.4 Dependence on Environment

Optimal scheme threshold parameters can depend on:
1. ARQ mode used
2. Underlying channel model
3. RS code speed
4. Delay

However, it does not mean that for every environment change the values of *T1* and *T2* have to change, too. Some changes were observed to have greater impact than other; the overview is presented in Table 2.

Table 2. Effect of environment change on scheme parameters

	T1	**T2**
ARQ mode	Yes	Partial; range <1; 5>
Channel model	Yes	No
RS code speed	Less significant	No

Delay changes were not investigated, as it exceeds the scope of this paper.

5.5 Considering Local Extremes

In the real communication system not all SNR values are present. In search of optimal results there might be several best values depending on investigated SNR range. Further analysis of performance parameter in Figure 8 reveals that beside result *T1*=80 we can also find other parameter - *T1*=115 whose throughput is shown in Figure 11 (image is zoomed in to improve visibility).

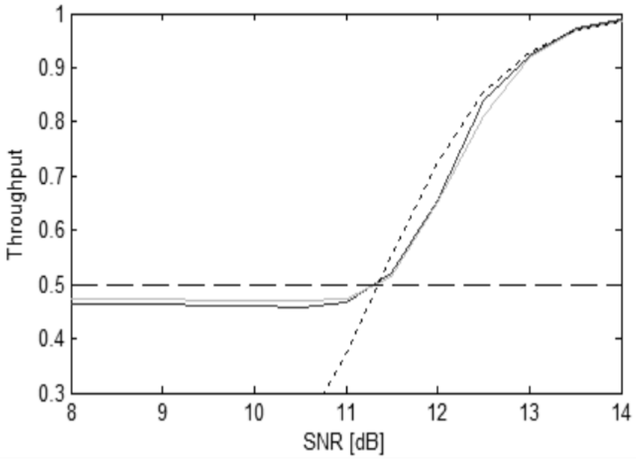

Figure 11. Two near-equal performance throughputs; **solid black** - ACK=80, NAK=2; **solid grey** - ACK=115, NAK=2

The scheme with parameter *T1*=115 has higher throughput in lower SNR values (HARQ domain) and, therefore, it can be a better solution for systems mostly requiring communication in a bad signal environment. But its throughput in ARQ domain is worse (this is the reason why it is not the best global solution).

To investigate such cases, SNR range can be specified in simulation that can exactly determine optimal parameters for given specific environment. For example, in SNR range 4-12 dB the value *T1*=115 is optimal, whereas the best value for SNR 8-18 dB is the global optimal value of *T1*=80.

Nevertheless, performance differences between optimal and locally optimal values are very small (95% vs. 93% of maximum local performance at 9 dB) and thus both can be considered as optimal.

6. Results

In Figures 12 - 15 we provide sample simulation results with parameters optimized for various channel settings.

The optimal threshold values for two main ARQ schemes using two different RS code settings are shown in Table 3.

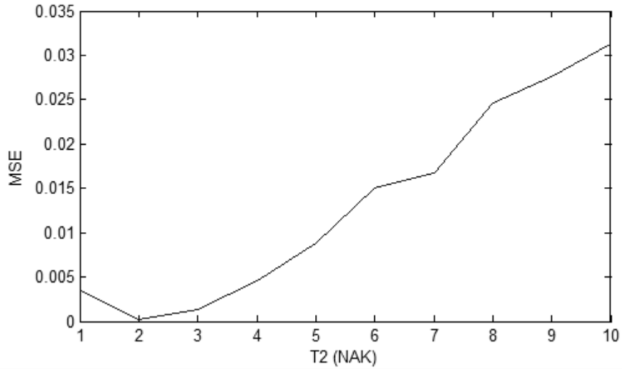

Figure 12. Optimization of parameter T2 in rural environment, GBN ARQ mode, RS[511, 383] and T1=150. You can see that for this environment optimal parameter value for T2 is 2 (with *MSE*(2)=0.00019).

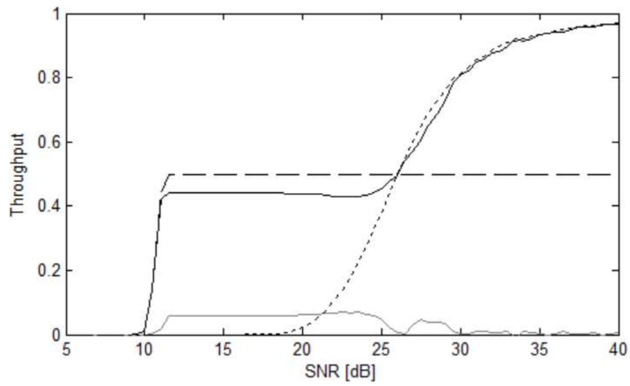

Figure 13. Optimized throughput in dependence of SNR for urban env, GBN, RS[511, 255]; **solid black** - ACK=45, NAK=2; **solid grey** - throughput difference from ideal ARQ/HARQ for urban env; **dashed** - ideal HARQ; **dotted** - ideal ARQ. Notice that throughput of HARQ scheme is slightly lowered in comparison to rural environment (Figure 10).

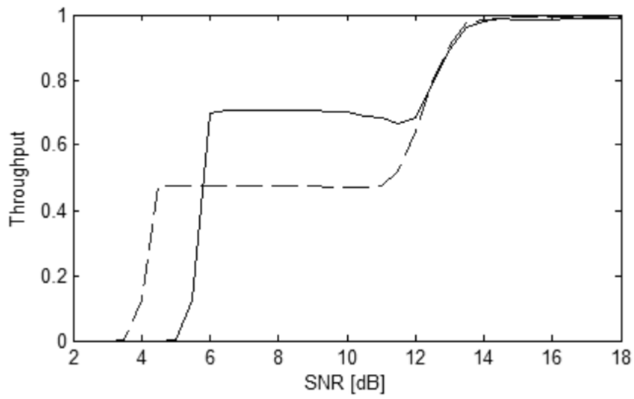

Figure 14. Throughput in dependence of SNR for two optimized schemes with different RS code in rural environment, GBN; **solid black** - RS[511, 383], ACK=150, NAK=2; **dashed** - RS[511, 255], ACK=80, NAK=2

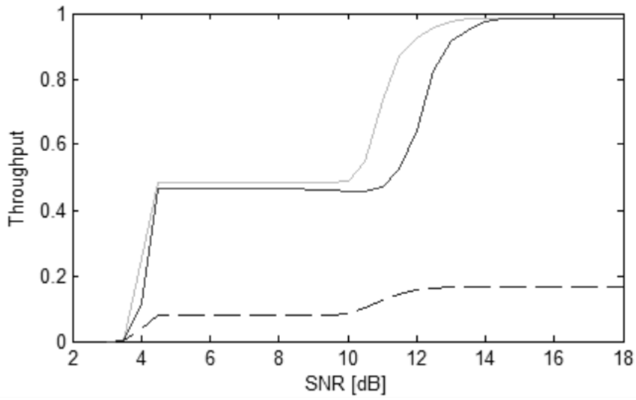

Figure 15. Throughput in dependence of SNR for all major ARQ schemes in rural env, RS[511, 255]; **solid grey** - Selective repeat, ACK=130, NAK=5; **solid black** - Go back N, ACK=80, NAK=2; **dashed** - Stop and wait, ACK=20, NAK=3

Table 3. Optimal values of T1 and T2 for rural environment

	GBN	SR
RS [511, 255]	ACK=80 NAK=2	ACK=130 NAK=5
RS [511, 383]	ACK=150 NAK=2	ACK=100 NAK=5

7. Conclusion

We proposed the scheme and the adaptation rule that estimates channel state by counting ACKs and NAKs. The described model for adaptive ARQ/HARQ method provides a very good throughput performance when threshold parameters are properly used and set up. The quick optimization of performance parameter allows us to find the best scheme parameters for various environments and transmission modes. Next attention could be focused on exploration of scheme's marginal error detection capability to be able to properly determine the best combinations of ARQ detection and HARQ correction codes and thus possibly to set up switching between more than two operation modes.

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