UMTS Turbo Decoder Dynamic Reconfiguration for Rural Outdoor Operating Environment

Costas Chaikalis
28 Areos Street,
13121 Ilion,
Athens, Greece
Tel. 00306934150364
c.chaikalis@ieee.org

Charalampos Liolios
Chantziskou 5 Street,
35100 Lamia,
Greece
Tel. 00306975857199
c.liolios@ieee.org

ABSTRACT
Quality of service (QoS) is an important task in the design of mobile communication systems. For UMTS system in order to realise a particular service, the QoS requirements in terms of performance and latency, have to be satisfied. Considering the QoS classification according to the priority of latency or performance, possible examples of service scenarios are examined for flat Rayleigh fading channels with emphasis on the turbo decoding algorithm. For rural outdoor operating environment considering SOVA and log-MAP turbo decoding algorithms due to their data-flow similarities, this paper shows that SOVA and log-MAP can be dynamically reconfigured. Particularly, SOVA represents the optimal choice for most of real-time applications, whereas for non-real time applications both algorithms are suitable except for low data rates and small frames where log-MAP is optimum.

Keywords
Mobile communications, turbo codes, SOVA, log-MAP, flat Rayleigh fading.

1. INTRODUCTION
Turbo codes where introduced in [1] and can be applied in any communication system where a significant performance improvement is required or the operating signal-to-noise ratio (SNR) is very low. Universal Mobile Telecommunications System (UMTS) belongs to the third generation (3G) of mobile communication systems. Turbo codes have been adopted as a channel coding scheme in UMTS for data rates higher or equal to 28.8 kbps. They have also been shown to provide very good coding gains in flat fading channels in the presence of outer block interleaving [2,3].The most important element of a turbo decoder is the soft-input/soft-output (SISO) decoder. Two candidate algorithms to be used in a SISO decoder are the soft output Viterbi algorithm (SOVA) and the log maximum a-posteriori (log-MAP) algorithm [2].

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Dynamic reconfiguration in wireless communications is a popular topic in published literature [4,5,6,7]. According to [8,9] and considering reconfiguration within a single wireless system (3GPP), particularly within the physical layer, we focus on the function of channel coding. A dynamic reconfigurable turbo decoder with increased efficiency can be derived according to the similarities in the data flow of SOVA and log-MAP, optimal in terms of performance and latency. The reason for considering just SOVA and log-MAP and not other candidate algorithms like max-log-MAP or MAP is that SOVA is optimum in terms of latency, while log-MAP is optimum in terms of performance [8,9].

2. UMTS PREVIEW AND SIMULATION ENVIRONMENT
In UMTS a transport channel transfers the information over the radio interface from the Medium Access Control sub-layer of layer 2 to the physical layer. The characteristics of a transport channel are determined by its transport format set, which consists of different transport formats. The transport formats must have the same type of channel coding and time transmission interval (TTI), while the transport block set or data frame size can vary. The transport block set determines the number of input bits to the channel encoder and can be transmitted every TTI, with possible values for TTI of 10, 20, 40 and 80 msec [10]. Furthermore, every transport channel is assigned a radio access bearer with a particular data rate.

Four different radio access bearer service traffic classes are defined: conversational, streaming, interactive and background. For real-time conversational and streaming classes the bit error rate (BER) has to be less than 10^{-3}, while for non-real time interactive and background classes it has to be less than 10^{-5}. The maximum acceptable latency for the conversational class is 80 msec, for streaming it is 250 msec, for interactive it is 1 sec, while for background it is higher than 10 sec [10].

The discrete representation of a flat Rayleigh fading channel is given by the following equation:

$$y_k = \alpha_k \cdot x_k + n_k \tag{1}$$

where k is an integer symbol index, x_k is a binary phase shift keying (BPSK) symbol amplitude (± 1), n_k is a Gaussian random variable and y_k is a noisy received symbol. The fading amplitude a_k is a sample from a correlated Gaussian random process with zero mean and is generated using the Sum of Sines or Jakes model [11].

In our simulations a carrier frequency $f_c = 2$ GHz is considered. It is also assumed that 1,000,000 information bits are transmitted and grouped into frames whose length k_f must be ≥ 40 and ≤ 5114, according to 3GPP specifications [10]. For a particular transport channel, every TTI the data with the characteristics specified in a transport format of the transport channel (k_f bits) is turbo encoded at the transmitter. After turbo encoding and block interleaving using the 3GPP parameters, the bits are BPSK modulated and transmitted through the mobile channel.

At the receiver, outer block deinterleaving and turbo decoding is performed. Furthermore, the received values are not quantized; therefore floating point arithmetic is used. The receiver is also assumed to have exact estimates of the fading amplitudes (perfect channel estimation without side information), while 8 iterations are used in the turbo decoder.

3. PROPOSED DECODER IMPLEMENTATION

Table 1. 3GPP transport channels (dynamic part)

Transport channel	*Dynamic part of Transport format set - Transport block sets (bits)*	*Data rate (kbps)*	*SNR (dB)*	*Scenario*
Dedicated channel	576, 1152	28.8	10	1
	576, 1152, 1728, 2304	57.6	9.5	2
	320, 640, 960, 1280	64	13	3
	320, 640, 1280, 2560	128	14	4
	320, 640, 1280, 2560, 2880	144	15	5

Table 2. 3GPP transport channels (semi-static part)

Transport channel	*Semi-static part of Transport format set*			*Data rate (kbps)*	*Scenario*
	Turbo encoder parameters		*TTI (msec)*		
	K	*Code rate*			
Dedicated channel	4	1/3	40	28.8	1
			40	57.6	2
			20	64	3
			20	128	4
			20	144	5

SOVA [2,12] and log-MAP [2,13,14] turbo decoding algorithms share common operations which have been addressed in [8,9]. These common operations lead to a turbo decoder which can be reconfigured and choose the optimum decoding algorithm according to the desired QoS.

Table 3. QoS (latency) for each scenario of Table 1 and 2

Scenario	*Class*	*Frame size*	*SOVA t_d (msec)*	*Log-MAP t_d (msec)*	*Max delay (msec)*
1	Streaming	576	240	528	250
	Non-real time classes	576	240	528	1 s interact., >10 sec background
		1152	400	976	1 s interact., >10 sec background
2	Streaming	576	160	304	250
		1152	240	528	250
	Non-real time classes	1152	240	528	1 s interact., >10 sec background
		1728	320	752	1 s interact., >10 sec background
		2304	400	976	1 s interact., >10 sec background
3	Conversational	320	80	152	80
	Streaming	320	80	152	250
		640	120	264	250
		960	160	376	250
		1280	200	488	250
4	Conversational	640	80	152	80
	Streaming	640	80	152	250
		1280	120	264	250
		2560	200	488	250
	Non-real time classes	2560	200	488	1 s interact., >10 sec background
5	Coversational	640	75.5	139.5	80
	Streaming	640	75.5	139.5	250
		1280	111.1	239.1	250
		2560	182.2	438.2	250
		2880	200	488	250
	Non-real time classes	2560	182.2	438.2	1 s interact., >10 sec background
		2880	200	488	1 s interact., >10 sec background

Table 4. QoS (BER) and optimum decoding algorithm for each scenario of Table 1 and 2

Scenario	*Frame size*	*SOVA BER*	*Log-MAP BER*	*BER range*	*Optimum algorithm*
1	576	$1.19x10^{-5}$	$2.99x10^{-6}$	$<10^{-3}$	SOVA
	576	$1.19x10^{-5}$	$2.99x10^{-6}$	$<10^{-5}$	Log-MAP
	1152	$5.99x10^{-6}$	$3.99x10^{-6}$	$<10^{-5}$	Log-MAP or SOVA
2	576	$1.5x10^{-4}$	$9x10^{-5}$	$<10^{-3}$	SOVA
	1152	$2.6x10^{-5}$	$7x10^{-6}$	$<10^{-3}$	SOVA
	1152	$2.6x10^{-5}$	$7x10^{-6}$	$<10^{-5}$	Log-MAP
	1728	$8x10^{-6}$	$5.8x10^{-6}$	$<10^{-5}$	Log-MAP or SOVA
	2304	$2x10^{-6}$	$1.8x10^{-6}$	$<10^{-5}$	Log-MAP or SOVA
3	320	$4.5x10^{-4}$	$3.6x10^{-4}$	$<10^{-3}$	SOVA
	320	$4.5x10^{-4}$	$3.6x10^{-4}$	$<10^{-3}$	Log-MAP or SOVA
	640	$7x10^{-5}$	$7x10^{-5}$	$<10^{-3}$	SOVA
	960	$3x10^{-5}$	$2.5x10^{-5}$	$<10^{-3}$	SOVA
	1280	$1.2x10^{-5}$	$1.1x10^{-5}$	$<10^{-3}$	SOVA
4	640	$2.5x10^{-4}$	$2x10^{-4}$	$<10^{-3}$	SOVA
	640	$2.5x10^{-4}$	$2x10^{-4}$	$<10^{-3}$	Log-MAP or SOVA
	1280	$7x10^{-5}$	$6x10^{-5}$	$<10^{-3}$	SOVA
	2560	$8.5x10^{-6}$	$8x10^{-6}$	$<10^{-3}$	SOVA
	2560	$8.5x10^{-6}$	$8x10^{-6}$	$<10^{-5}$	Log-MAP or SOVA
5	640	$1x10^{-4}$	$7.99x10^{-5}$	$<10^{-3}$	SOVA
	640	$1x10^{-4}$	$7.99x10^{-5}$	$<10^{-3}$	Log-MAP or SOVA
	1280	$3.59x10^{-5}$	$3.29x10^{-5}$	$<10^{-3}$	Log-MAP or SOVA
	2560	$9.99x10^{-7}$	$9.99x10^{-7}$	$<10^{-3}$	SOVA
	2880	$1.99x10^{-6}$	$1.99x10^{-6}$	$<10^{-3}$	SOVA
	2560	$9.99x10^{-7}$	$9.99x10^{-7}$	$<10^{-5}$	Log-MAP or SOVA
	2880	$1.99x10^{-6}$	$1.99x10^{-6}$	$<10^{-5}$	Log-MAP or SOVA

Tables 1 and 2 illustrate five different 3GPP dedicated transport channels with different transport format (TF) sets, which represent different implementation scenarios of the reconfigurable SOVA/log-MAP turbo decoder. The TF set for each transport channel consists of different example TF and also of dynamic and semi-static parts [10]. Therefore, Table 1 shows the dynamic part and Table 2 the semi-static part of the scenarios. Moreover, as published simulation results have shown ([2,3]), in flat Rayleigh fading channels data rate, outer block interleaving (thus TTI) and SNR greatly affect the BER. Therefore, for each scenario of Table 1 and 2 these three parameters differ, considering also the examples described in [15].

According to [10], for UMTS standard and rural outdoor operating environment the maximum supported mobile speed is 500 km/h and the maximum data rate 144 kbps. A mobile speed of 500 km/h corresponds to high speed vehicles like trains. Thus, a more typical value for this environment is 300 km/h.

Each implementation scenario of the reconfigurable decoder of Table 1 and 2 is applied to rural outdoor operating environment, where we consider a value of the mobile terminal speed of 300 km/h.

Similarly to [8,9], for the calculation of the total maximum latency per frame for SOVA and log-MAP we assume pipeline turbo decoder architecture and a processor that runs at the same rate for both algorithms. Thus for SOVA we have:

$$t_d = 2 \times TTI + \left(\frac{k_f}{R_b} \times N \right) \qquad (2)$$

Similarly, for log-MAP the total maximum latency is given by:

$$t_d = 2 \times TTI + \left(\frac{k_f}{R_b} \times N \times 2.8 \right) \qquad (3)$$

where t_d is the total latency, k_f is the frame size, R_b is the bit rate of the radio bearer assigned to the transport channel and N is the number of turbo decoder iterations. In these equations the higher complexity of log-MAP compared to SOVA (2.8 times) is also considered.

The two QoS parameters that determine the choice of the optimum decoding algorithm are performance and latency. Therefore, for each scenario of Table 1 and 2 all four service classes are applied in order to determine the QoS profile parameters for different applications. Latency is calculated using equations (2) and (3), while the simulated BER performance for each scenario is given in the following section. Particularly, for rural outdoor operating environment Table 3 and 4 show the QoS for the different frame lengths for each scenario: the analysis of the results follows. It must be mentioned that the analysis shown on Table 3 considers the latency part of QoS, while Table 4 considers the BER part of QoS. Finally, it has to be mentioned that for each scenario only the frames that satisfy the QoS parameters are shown in Tables 3 and 4.

4. SCENARIOS ANALYSIS FOR RURAL OUTDOOR OPERATING ENVIRONMENT

4.1 Scenario 1: 28.8 kbps radio bearer service

Figure 1 presents the simulation results for this scenario. The following parameters are assumed: $R_s = 86.4$ Kbaud, $f_d T_s = 0.0064$ with $f_d = 555.5$ Hz, TTI=40 msec. A signal-to-noise ratio of 10 dB is also considered (see Table 1). The conversational class is not considered at this particular signal-to-noise ratio due to its high latency for both frames.

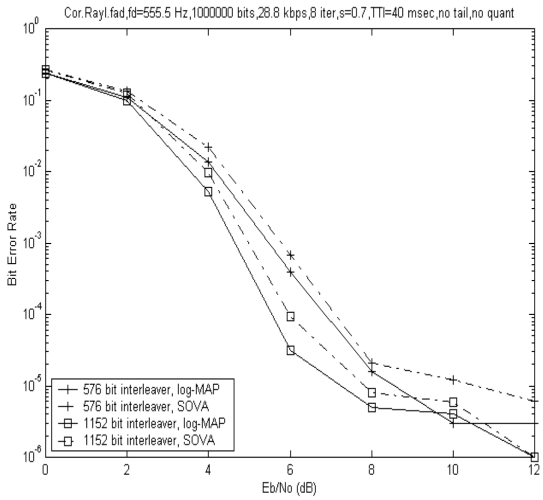

Figure 1. BER vs SNR for scenario 1

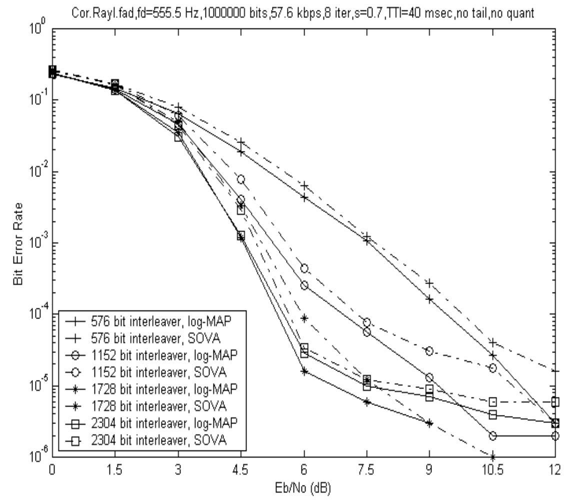

Figure 2. BER vs SNR for scenario 2

4.1.1 Streaming service class

According to Tables 3 and 4, only the 576-bit frame can be implemented and SOVA is the optimum choice.

4.1.2 Interactive/background service classes

Tables 3 and 4 show that there is no optimum decoding algorithm for a frame of 1152 bits because both algorithms satisfy the two requirements. For a frame of 576 bits log-MAP is the suitable algorithm since it is the only one to satisfy the low bit error rate constraint.

4.2 Scenario 2: 57.6 kbps radio bearer service

Figure 2 shows the bit error rate performance for the different frames tailored to this scenario according to Table 1. The following parameters are used for the generation of the simulation results: $R_s = 172.8$ Kbaud, $f_d T_s = 0.0032$ with $f_d = 555.5$ Hz, TTI=40 msec and a signal-to-noise ratio of 9.5 dB. Similarly to the previous section, no frame lengths of conversational class are considered because of the high latencies.

4.2.1 Streaming service class

As Table 3 and 4 displays, SOVA is the optimum choice for 576 and 1152 bits, while the other two frame lengths cannot be implemented.

4.2.2 Interactive/background service classes

Table 3 and 4 illustrate that the three frame lengths give very low bit error rate so that they can be implemented in the two non-real time classes. Particularly, for frame lengths of 1728 and 2304 bits both algorithms can be used, while in the case of 1152 bits log-MAP is optimum.

4.3 Scenario 3: 64 kbps radio bearer service

Figure 3 presents the simulation results for this scenario. The following parameters are assumed: $R_s = 192$ Kbaud, $f_d T_s = 0.0028$ with $f_d = 555.5$ Hz, TTI=20 msec. Our analysis shows that only the real-time classes are considered, whereas the non-real time classes cannot be implemented because for all the frame lengths the desired bit error rate cannot be achieved at the signal-to-noise ratio of 13 dB.

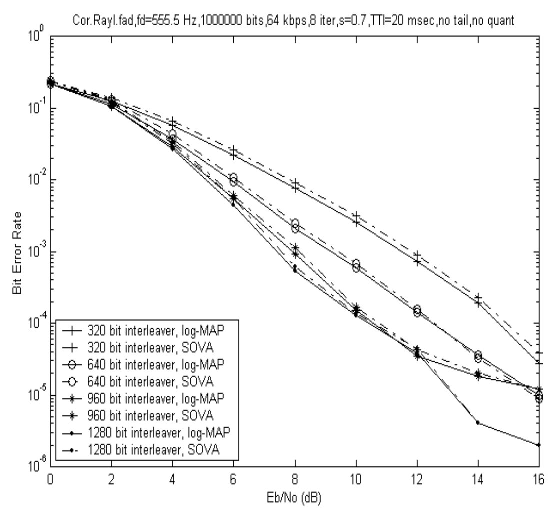

Figure 3. BER vs SNR for scenario 3

4.3.1 Conversational service class

According to Table 3 and 4 for a frame length of 320 bits SOVA is optimum, while the other frame lengths give too high latency to be implemented.

4.3.2 Streaming service class

For streaming class and a small frame of 320 bits both algorithms can be used. On the other hand, for larger frame lengths SOVA is the best solution because log-MAP exceeds the maximum acceptable latency value for this class. The bit error rate requirements are achieved from both algorithms for all frame lengths.

4.4 Scenario 4: 128 kbps radio bearer service

For Figure 4 the following parameters are assumed: $R_s = 384$ Kbaud, $f_d T_s = 0.0014$ with $f_d = 555.5$ Hz, TTI=20 msec and a signal-to-noise ratio of 14 dB. Figure 4 demonstrates the bit error rate performance for the different frame lengths specified in Table 1 for this scenario. Our Table 3 and 4 analysis shows that all four service classes can be applied.

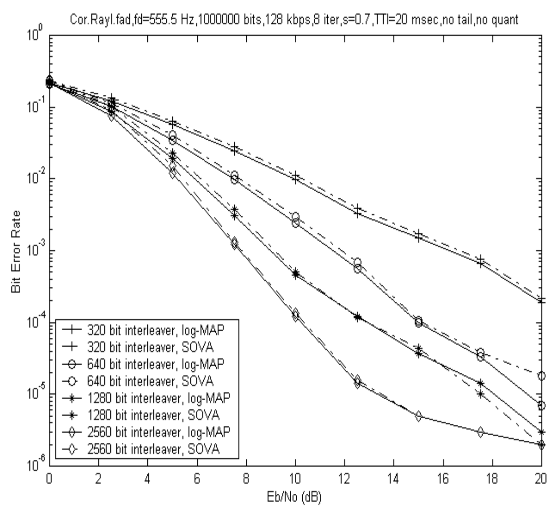

Figure 4. BER vs SNR for scenario 4

4.4.1 Conversational service class

For conversational class only the small frame length of 640 bits can be implemented. The bit error rate performance of both algorithms is within the bit error rate range, but SOVA is optimum because log-MAP exceeds the latency limit. For frame lengths of 1280 and 2560 bits the latency is too high for either algorithm. In the case of 320 bits the bit error rate is too high to satisfy the requirements.

4.4.2 Streaming service class

For this class and for 14 dB a frame of 320 bits cannot be implemented for either SOVA or log-MAP because the bit error rate is too high. For 640 bits either SOVA or log-MAP can be used because both satisfy the two requirements. For frames of 1280 and 2560 bits SOVA is optimum because the latency of log-MAP is too high to satisfy the requirements.

4.4.3 Interactive/background service classes

For the two non-real time classes only the frame of 2560 bits can be considered because for the other frame lengths of this dedicated transport channel the bit error rate requirements cannot be satisfied. In the case of 2560 bits either SOVA or log-MAP can be used since both criteria are satisfied.

4.5 Scenario 5: 144 kbps radio bearer service

For Figure 5 the following parameters are assumed: $R_s = 432$ Kbaud, $f_d T_s = 0.0012$ with $f_d = 555.5$ Hz and TTI=20 msec. Figure 5 shows the bit error rate performance for the different frame lengths specified in Table 1 for this scenario. Again, all four service classes can be applied for this scenario and the signal-to-noise ratio of 15 dB.

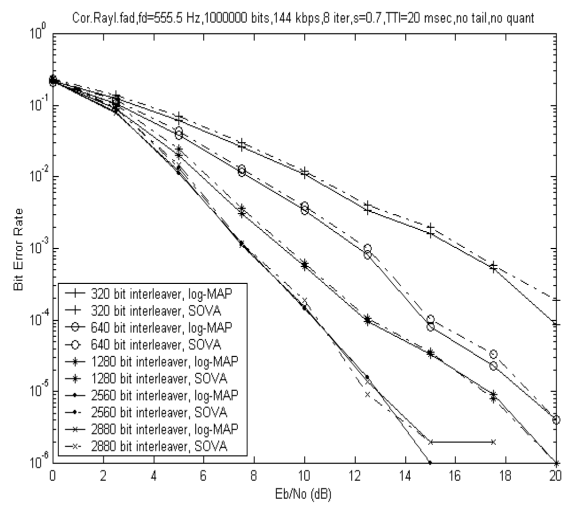

Figure 5. BER vs SNR for scenario 5

4.5.1 Conversational service class

Table 3 and 4 show that SOVA is optimum for 640 bits frame length. In this case log-MAP gives too much latency. For 320 bits the bit error rate requirements are too low for either algorithm. On the other hand, for the other frames latency is too low for either SOVA or log-MAP.

4.5.2 Streaming service class

For low frame lengths (640 and 1280 bits) either algorithm satisfy the bit error rate and latency criteria. For higher frames (2560 and 2880 bits) SOVA is optimum because of the large log-MAP delays. The case of 320 bits is not considered because the two criteria are not satisfied for either algorithm.

4.5.3 Interactive/background service classes

Table 3 clearly shows that either algorithm can be used for the non-real time classes and for frame lengths 2560 and 2880 bits. For the other frame lengths the bit error rate range is too tight to be achieved by either SOVA or log-MAP.

Let's give a summary for the results presented in this section. It is observed that for rural operating environment, non-real time classes and low rates (≤57.6 kbps) relatively small frames (e.g. 576, 1152 bits) can be established together with the other frame lengths. In this case log-MAP is optimum for the small frames, whereas SOVA and log-MAP are equally suitable for larger frames. For increased rates (>57.6 kbps) only large frames can be established with SOVA and log-MAP being equally suitable.

For real-time class we observe the following: conversational real-time class can be applied to small frames (e.g. 320, 640 bits) and low or medium data rates (64, 128, 144 kbps). Here, the choice of the optimum algorithm does not depend on the operating environment: SOVA is optimum in all cases. In the case of streaming real-time class applications for low data rates (≤57.6 kbps) SOVA is optimum for all frames. For increased data rates (>57.6 kbps and ≤144 kbps) either algorithm can be used for relatively small frames, with SOVA being optimum for larger frames. It is interesting to note that as the data rate increases more and larger frames can be applied for this service class.

5. CONCLUSIONS

In a turbo decoder SOVA represents the best choice in terms of complexity, while log-MAP is the best choice in terms of performance. In [8,9] the idea of a reconfigurable SOVA/log-MAP turbo decoder is introduced. Additionally, in [8,9] the operations of the two algorithms were analysed showing that there are similarities in the data-flow.

For UMTS mobile communications some applications require the lowest possible latency, while for others the lowest possible performance is sufficient. Most implementation scenarios in flat Rayleigh fading channels and rural outdoor operating environment (300 km/h mobile terminal speed) show that there is an optimum algorithm, although there are cases where both algorithms are equally suitable. Particularly, the different implementation scenarios show that in the case of real-time applications, where latency is the priority and performance requirements are looser, SOVA is the optimum choice in the majority of scenarios. Nevertheless, for a streaming service class, as the data rate increases the number of frames that both algorithms are equally optimal increases as well: at medium data rates for small or medium frames and at high data rates for all frames both algorithms are equally optimal. It is also interesting to observe that for rural outdoor operating environment more frames can be established compared to similar work which have been done for urban/suburban outdoor environment in [16]. The reason is the better performance the algorithms can achieve.

In the case of non-real time applications performance is the priority and latency requirements are looser. Here, at low data rates and for small frames log-MAP represents the optimal choice. Nonetheless, either SOVA or log-MAP can be used in all other cases. According to [2] and as our simulation results have shown, the reason is that at high signal-to-noise ratios and low bit error rates the two algorithms exhibit almost the same performance.

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