CAN AN ADDED VALUE BE OFFERED TO SDR OPERATORS IN SCENARIOS WHERE INTEROPERABILITY TO LEGACY RADIOS IS A REQUIREMENT?

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ABSTRACT

The novel *Software Defined Radio* (SDR) technology allows taking the next step in the evolution of military tactical communications. SDRs allow military radio operators to change waveforms on-the-fly according to the mission needs. On the one hand, new wideband networking waveforms will offer new services like high data throughputs and MANET capabilities. On the other hand, legacy waveforms will ensure interoperability to legacy equipment in missions where both types of radios are deployed at the same time.

In this paper, we analyze if an added value can be provided to the operators at SDRs hosting an 'enhanced' legacy waveform. This enhancement shall be introduced such that interoperability to the legacy equipment is still guaranteed.

We show that higher error robustness can be realized if the modern concepts of *Hierarchical Modulations* and *Incremental Redundancy* are applied in the porting process of legacy waveforms to SDRs. The modulation scheme of the legacy waveform acts as the *base-layer* in the hierarchical modulation scheme ensuring interoperability to legacy equipment, while additional error protection information is transmitted between SDRs on some extra *enhancement-layers*.

1. INTRODUCTION

The capabilities of military tactical communications will considerably be enhanced by fielding the future modern *Software Defined Radio* (SDR) technology. Besides many other advantages of SDR technology, one key benefit is that SDRs allow loading different types of waveforms as so-called *Waveform Applications* (WFA) according to the mission needs. Thanks to the extended computational resources SDRs will allow hosting modern WFAs with, e.g., wideband networking capabilities. Such *Wideband Networking Waveforms* (WNW) will typically set the most demanding constraints for the design of high capable heterogeneous SDR platforms. However, whenever legacy WFAs with less computational demands are deployed on SDRs, most of the computational capacities remain unused. In this paper, we will discuss an approach to beneficially use these spare resources by applying advanced signal processing algorithms.

The key motivation for our analysis is that it can be anticipated that SDR technology will not replace legacy radios all at once. SDRs will most probably be introduced in a step-by-step process to military forces. There will be a significant period of time where legacy radios and modern SDRs hosting the ported legacy WFA will be deployed at the same time in the same mission. Porting in this context means that the waveform functionality which is known from the legacy radio is implemented as a piece of software which runs on the SDR platform. This piece of software is called *Waveform Application* (WFA). Usually, in order to guarantee interoperability the known functionality of the legacy radios is reproduced one-to-one as WFA for SDRs.

However, we have already proposed in [1] and [2], that it might be beneficial to apply modern advancements in digital signal processing in the WFA representation of the legacy system. Of course, these new algorithms may not have any adverse effect on the interoperability on the air interface.

In order to guarantee interoperability, in our analysis presented in [1], we focused on modifications to the receiver side only. With this, the key objective has been to offer the operator at the receiving SDR an added value if compared to the operator at the legacy radio thanks to the more sophisticated receiver signal processing. Such a benefit might be made available, e.g., in a reduced bit error rate or an extended communication range. In [1], we have applied the concept of *Bit Interleaved Coded Modulation with Iterative Decoding* (BICM-ID) [3][4] to the receiver using some MIL-STD188-110B-like waveform modes [5] as an example. It has been shown that some gains are achievable, but unfortunately that these gains have to be considered as negligibly small if the concept of BICM-ID is directly applied to the standardized configuration settings. It has also

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been shown that substantial gains can be realized if a change of a single line of software code at the transmitter is tolerable. Of course, this would violate the key requirement to guarantee interoperability to legacy radios.

In [2], we have extended these considerations to a system where changes in the transmitting end do not necessarily result in a loss of interoperability. For this purpose, we have analyzed the concept of *Hierarchical Modulation* [7] [8]. Using the known configuration settings from the legacy waveform as a *base-layer* in the hierarchical modulation scheme, allows ensuring interoperability between legacy radios and SDRs. Thanks to some extra *enhancement-layers* in the hierarchical modulation scheme additional data becomes transferable within an SDR-to-SDR communication link. This additional data budget can either be used to increase the data rate resp. throughput or to increase error robustness (and with this communication range). In [2], we have focused on the first case.

The present paper can be considered as a complementing paper to [2]. We will analyze the second case in detail. As a novelty, we will consider the concept of *Incremental Redundancy* to increase error robustness [9]. Typically, this concept is used in *Hybrid Automatic Repeat Request* (HARQ) schemes. Whenever a retransmission of data becomes necessary extra error protection information, which is different from the original transmission, will be send. In the present paper those (re)transmission shall happen inherently by exploiting the *enhancement-layers* of the hierarchical modulation scheme.

This paper is structured as follows. In Section II we will review the idea of *Hierarchical Modulation* in the context of legacy waveforms on SDRs [2]. In Section III we will describe the proposed simulation environment taking into account both concepts, *Hierarchical Modulation* and *Incremental Redundancy*. Some simulations results will be presented in Section IV. In Section V, we will present a convergence analysis using EXIT charts [12]. We will finally conclude our findings in Section VI.

2. HIERACHICAL MODULATION IN THE CONTEXT OF LEGACY WAVEFORMS ON SDRS

Hierarchical Modulation allows multiplexing and modulating multiple streams of user data to a single stream of modulation symbols. It is sometimes also referred to as *Layered Modulation* because one of the input data streams determines the *base-layer* symbols and the other input data streams determine the extra *enhancement-layer* symbols.

One prominent practical implementation of *Hierarchical Modulation* can be found in *Digital Video Broadcasting* (DVB) [8] where the *base-layer* carries information of a robust, but typically low-resolution video stream. Extra *enhancement-layers*, which might only be decodable by receivers under good channel conditions, allow to increase the resolution and therewith the quality of the video.

As originally introduced in [2], our basic idea is to apply a similar technique in the porting process of legacy waveforms to modern software defined radios. In the ported counterpart of the legacy waveform, the information of the legacy waveform represents the *base-layer* guaranteeing interoperability. On top of that the operators at SDRs can transmit additional data using the extra *enhancement-layers*.

In [2] we have exploited this extra bit budget to transmit more user data and with this to increase the user's data throughput. In contrast, in the present paper we exploit it to increase the error robustness (and with this to increase communication range).

2.1 Example Base-Layer and Enhancement-Layers

To simplify matters, in the following we restrict our considerations to a comprehensible example using an 8-PSK signal constellation as base-layer. Such a digital modulation scheme is widely used in a couple of present military tactical communication schemes like in NATO STANAG 4285 [6] or MIL-STD188-110B Appendix C [5]. The extension of our considerations to other digital modulation schemes is straightforward.

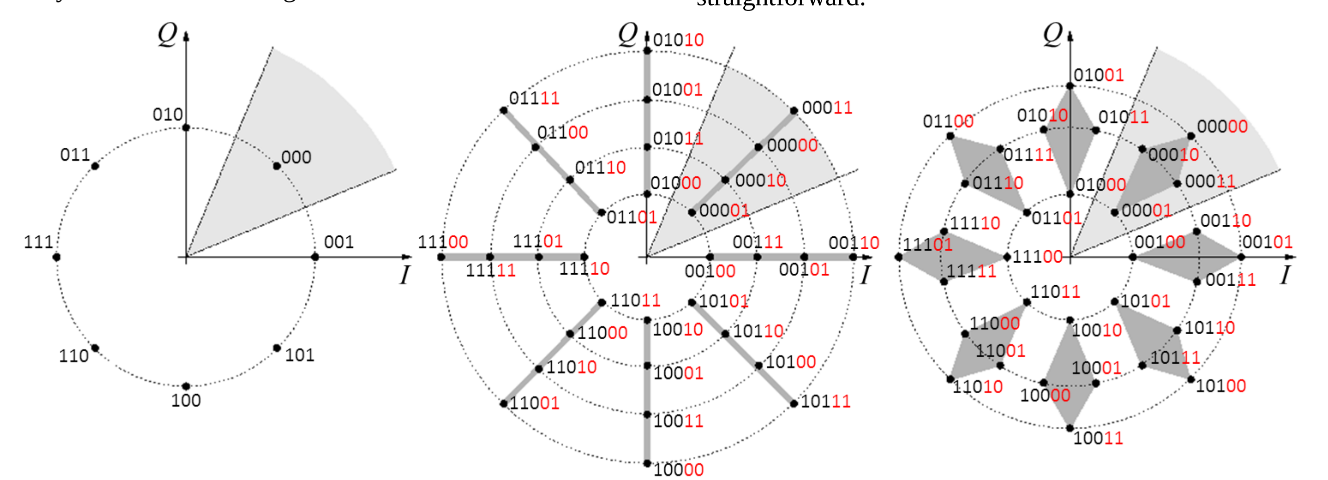

Figure 1: Different Signal Constellation Sets [2] with exemplary symbol labels; left: 8-PSK *base-layer*, center: 8-PSK *base-layer* plus 4-ASK *enhancement layer* (star); right: 8-PSK *base-layer* plus 4-QAM *enhancement layer* (diamonds)

The left part of Figure 1 shows an 8-PSK signal constellation set with a classic *Gray* labeling for the individual symbols. This set shall serve as the *base-layer* for our hierarchical modulation schemes. Note, in this simple example, the *base-layer* carries information solely in its phase.

In order to provide an add-on to the operators at SDRs we are aiming for transmitting some additional data in so-called *enhancement-layers*. Two examples (taken from [2]) are shown in the center and in the right part of Figure 1.

In the first example, we apply a 4-ASK *enhancement-layer* as an overlay to the 8-PSK *base-layer*. This results in an overall 32-QAM scheme which would allow the operator at the SDR to transmit two additional bits. Simply speaking, the *base-layer* selects one of the eight sectors in the I/Q-plane (inphase/quadrature) while the *enhancement-layer* selects one out of four magnitudes in each sector. Later on, this scheme will also be referred to as "*star-shaped*" 32-QAM scheme.

In the second example (shown on the right of Figure 1) we again apply an *enhancement-layer* with 4 signal constellation points to the 8-PSK base-layer. However, inspired by [7] the slightly different placing of signal constellation points allows exploiting the I/Q-plane more effectively. In the rest of this paper, this scheme will be called "*diamond-shaped*" 32-QAM scheme.

2.2 Rules for Designing the Enhancement-Layers

The details for the optimal placing of signal constellation points have been derived in [2] for both 32-QAM schemes. The design rules for the enhancement-layer are:

- The mean energy E_S required per modulation symbol shall be the same for the original 8-PSK scheme and the extended *star-* resp. *diamond-shaped* 32-QAM.
- The Euclidean distance between any pair of signal constellation points shall be such that not a single pair exists which reveals a dedicated bottleneck with respect to the *Bit Error Rate* (BER) performance.
- The symbol labels shall be optimized in view of a receiver using the concept of *Bit-Interleaved Coded Modulation with Iterative Decoding* (BICM-ID) [3][4].

The first two design rules are related to the placing of signal constellation points in the I/Q-plane while the third design rule is dedicated to the labeling. Both aspects had been optimized separately from each other in [2].

2.3 Optimal Placing of Signal Constellation Points

We have shown in [2] that the optimal radii for the signal constellation points fulfilling the first two design rules are

$$\begin{array}{l} r_1^*=0.432499 \\ r_2^*=0.763499 \\ r_3^*=1.094499 \\ r_4^*=1.425499 \end{array} \quad \rightarrow \text{with } \alpha^* = 0.331 \qquad (1)$$

for the *star-shaped* 32-QAM scheme and

$$\begin{array}{l} r_1^{\Diamond}=0.5098 \\ r_2^{\Diamond}= r_3^{\Diamond}=1.0001 \\ r_4^{\Diamond}=1.31878 \end{array} \quad \rightarrow \text{with } \alpha^{\Diamond} = 0.3902 \qquad (2)$$

for the *diamond-shaped* 32-QAM scheme. The terms α* resp. $\alpha^{\Diamond}$ determine the minimum Euclidean distance between any combination of two signal constellation points. Notice, the minimum Euclidean distance $\alpha^{\Diamond}$ in the *diamond-shaped* 32-QAM scheme is slightly higher than α^* for the *star-shaped* 32-QAM scheme. This might offer a potential for a higher performance as it will be discussed in more detail in Section IV. (Remark: α = 0.7654 for the 8-PSK scheme.)

2.4 Optimal Labels for Signal Constellation Points

The symbol labels for both 32-QAM schemes have been chosen such that a receiver design based on the BICM-ID concept is optimally supported.

The concept of BICM-ID was first described in [3] and is based on a serial concatenation of a *Forward Error Correction* (FEC) component, a bit-level interleaver and a digital modulation scheme. On the receiving end, there is a feedback loop between the BCJR-decoder [11] and the demodulator. So-called *Extrinsic Information* generated by the BCJR-decoder is interleaved and then fed back to the demodulator as additional *a priori* information for the received channel symbols.

It has already been shown in [4] that the BICM-ID concept is optimally supported if a so-called *Semi Set Partitioning* (SSP) symbol labeling is applied. For a given signal constellation the SSP mapping ensures that the so-called *Harmonic Mean* d_H [4] is maximized. Table I shows the *Harmonic Means* for all signal constellations under consideration in this paper. The corresponding optimal symbol labelings can be found in Figure 1.

TABLE I. HARMONIC MEANS FOR DIFFERENT SIGNAL CONSTELLATION SETS

	Signal Constellation Set	Harmonic Mean d_H
Restricted SSP	8-PSK (Gray)	0.809
	Star-shaped 32-QAM	0.470
	Diamond-shaped 32 QAM	0.403
Free-running SSP	8-PSK (SSP)	2.877
	Star-shaped 32-QAM	2.501
	Diamond-shaped 32 QAM	2.520

Notice, if we would have been totally free in designing the symbol labeling the maximum achievable values are given in the lower part of Table I (marked as *free-running SSP*). It can be seen that, besides the better $\alpha^{\Diamond} > \alpha^*$ mentioned above,

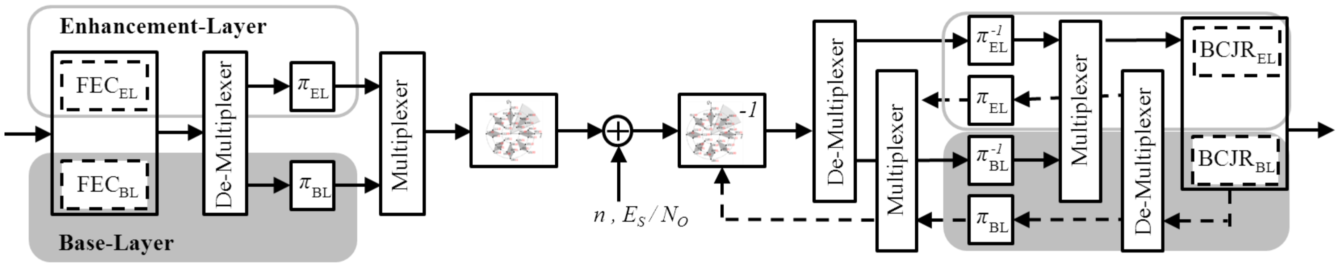

Figure 2: Block diagram of simulation environment with *base-layer* and *enhancement-layer* signal processing

the *diamond-shaped* 32-QAM also offers a slightly higher *Harmonic Mean* d_H if compared to the *star-shaped* 32-QAM. A comparison to the optimal d_H for the 8-PSK constellation with a free-running SSP is not fair because due to the higher number of signal constellation points in the 32-QAM schemes, the Euclidean distances (which are taken into account by the Harmonic Mean) are typically smaller.

However, since we have to ensure interoperability to legacy radios we are not totally free in the design of the symbol labeling. We have to take into account the labeling of the original 8-PSK scheme. For instance, in case of the 4.8 kbps mode of MIL-STD188-110B Appendix C [5] the original labeling is given by a Gray labeling (see left part of Fig. 1).

When designing the labels for the 32-QAM schemes we have to make sure that the labels of the *base-layer* are part of the overall labels. For the given example considered here that means that the *Gray* labeling of the 8-PSK scheme determines the three leftmost bits in the overall five bit long labels for the 32-QAM schemes. Taking this restriction into account yields the *Harmonic Mean* values mentioned in the upper part of Table I. Obviously, the restriction results in significantly smaller *Harmonic Mean* d_H values if compared to the free-running optimization approach. Consequently, the attainable performance gains will be significantly smaller. Surprisingly, the restricted *Harmonic Mean* $d_H^*=0.470$ for the *star-shaped* 32-QAM scheme is higher than $d_H^{\diamond}=0.403$ for the *diamond-shaped* 32-QAM scheme.

3. SIMULATION ENVIRONMENT

In the following, the pros and cons of considering the concepts of *Hierarchical Modulation* and *Incremental Redundancy* in the porting process of legacy waveforms to SDRs shall be analyzed using a simulation example. For this purpose we use a simulation environment as shown in Fig. 2. The *base-layer* (i.e., the legacy system) shall resemble the 4.8 kbps mode of MIL-STD188-110B Appendix C [5].

3.1 Legacy Transmitter resp. Base-Layer only

In the 4.8 kbps mode of MIL-STD188-110B Appendix C [5] the input data is at first encoded by a rate $R=1/2$, constraint length $L=7$ convolutional mother code with generator polynomial $G=\{133,171\}_8$. The codewords are punctured to $R_p=3/4$ using the puncturing pattern *(1,1; 1,0; 0,1)*.

The punctured codewords are block interleaved using one out of several possible interleaver sizes. The interleaver size is mainly determined by the maximum acceptable delay on the communication link and it must be a multiple *i* of *768* bits (with *i=1,3,9,18,36,72*).

In contrast to the original 4.8 kbps mode of MIL-STD188-110B Appendix C [5] in this paper we neglect aspects like scrambling or synchronization. We focus on an interleaver size of *6912* only, i.e. *i=9*. Instead of a full tail-biting convolutional code we use a terminated convolutional code. Anyhow, we assume that none of these modifications has a major impact on the relevance of our findings for an established real-world legacy system.

3.2 Combination of Base-Layer and Enhancement-Layer

Thanks to the *hierarchical modulation* scheme with the signal constellation sets shown in the center and on the right of Figure 1, the *enhancement-layer* allows transmitting 2 extra bits per symbol.

In contrast to [2], in the present paper this spare bit budget is not utilized for transmitting extra user data (e.g. to improve user's data throughput), but it is used for extra error protection information (reducing the bit error rate can typically also be interpreted as extending communication range). This extra error protection information shall be chosen such that the constraints of *Incremental Redundancy* are fulfilled [9] [10]. That means, parity check information which is different from the one of the *base-layer* shall be transmitted on the *enhancement-layer*.

The extra error protection information on the *enhancement-layer* is interleaved separately from the *base-layer* by a so-called *S*-random interleaver of size *4608* (which is *2/3* of the interleaver size on the *base-layer*, i.e. *2/3* of *6912*). This extra error protection information results from a powerful rate $R=1/3$, constraint length $L=7$ convolutional mother code with generator polynomial $G=\{133,171,165\}_8$.

Notice, if we apply a puncturing pattern of *(1,1,0; 1,0,0; 0,1,0)* to the $R=1/3$ code we get the same $R_p=3/4$ code as given in the 4.8 kbps mode of MIL-STD188-110B Appendix C. Thus, this puncturing pattern is applied for the bit stream provided to the *base-layer* processing steps. In addition, we apply the puncturing pattern of *(0,0,0; 0,1,0; 1,0,1; 0,0,0; 0,1,0; 1,0,0; 0,0,1; 0,1,0; 1,0,0)* to the *R=1/3* code to get some incremental redundancy to the *base-layer* information which is transmitted on the *enhancement-layer*. The overall forward error correction scheme has an effective rate of $R_{eff}=9/20$ which comes close to the original rate *R=1/2* mother code.

Remember, the error correction capabilities of convolutional codes are determined by the minimum free distance d_{free}. The minimum free distance of the original *R=1/2* mother code with $G=\{133,171\}_8$ is $d_{free}=10$. Due to puncturing to $R_p=3/4$ it had been decreased to $d_{free}=5$. The rate *R=1/3* code with $G=\{133,171,165\}_8$ has a $d_{free}=15$. Note, with respect to our design of the puncturing patterns, we can expect that the effective $R_{eff}=9/20$ code under consideration in our hierarchical modulation scheme will offer a minimum free distance of $d_{free}\geq 10$, but smaller than $d_{free}<15$.

3.3 Transmission Channel and Receiver Processing

As transmission channel serves an *Additive White Gaussian Noise* (AWGN) channel with known E_S/N_O where E_S determines the energy per modulation symbol and N_O the power spectral density of the AWGN. At the receiving end of our simulation chain we apply the concept of BICM-ID jointly to both, the *base-layer* and the *enhancement-layer*. Note, the demodulation as well as the BCJR-decoding [11] are illustrated as one block each in Figure 2. Only the communication between both blocks is realized separately due to the two interleavers. Of course, both interleavers of sizes *6912* and *4608* can also be combined to a single interleaver of effective size *11520*.

The behavior of a legacy radio is inherently included by decoding the *base-layer* without any BICM-ID iteration (i.e., no feedback loop in Figure 2).

4. SIMULATION RESULTS

Figure 3 shows some exemplary simulation result where we use the effective rate $R_{eff}=9/20$ code in combination with both the 32-QAM schemes. The performance of the legacy system with the *R=3/4* code and the 8-PSK signal constellation set is shown in black as a reference.

The simulation results in Figure 3 show that thanks to the stronger error protection scheme an added value in terms of higher robustness (and with this, typically an extended communication range) can be provided to the SDR operator. A single iteration is sufficient to provide a gain if compared to the legacy 8-PSK scheme. After 5 Iterations gains of more than 3 dB in E_S/N_O can be realized. The additional gains for higher numbers of iterations become negligibly small.

Surprisingly, the performances for both 32-QAM schemes are quite similar. The sharp bend in the BER curves at an E_S/N_O of approximately 7 dB is due to the bound given in case of errorfree feedback (error floor). This error floor is slightly better for the *star-shaped* 32-QAM scheme because the restricted *Harmonic Mean* $d_H^*=0.470$ was higher than $d_H^\Diamond=0.403$ for the *diamond-shaped* 32-QAM scheme.

Generally, a loss of up to 1.7 dB in E_S/N_O has to be accepted if no iterations are carried out. From that we can conclude that the concepts of *Hierarchical Modulation* and *Incremental Redundancy* can only be beneficially applied in the porting process of legacy waveforms if at the same time the BICM-ID concept is realized at the receiving end.

The simulation results shown in Figure 3 reveal that a gain can be realized in SDR-to-SDR communication links. However, as already analyzed in detail in [2], a loss has generally to be tolerated in mixed scenarios, i.e. SDR-to-Legacy- resp. Legacy-to-SDR communication links. The

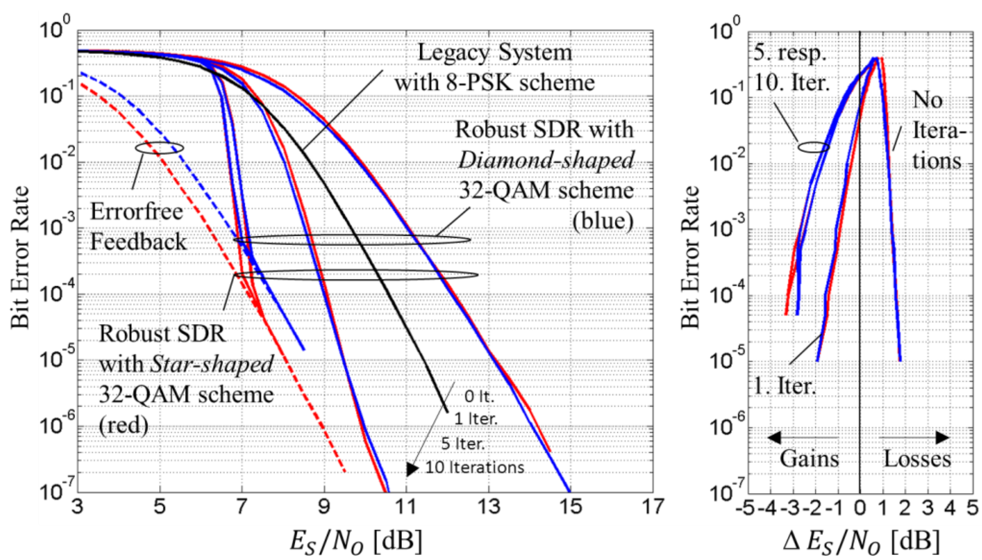

Figure 3: BER performance of robust SDR schemes transmitting extra error protection information on the *enhancement-layer*

loss is roughly the same as the gain which we can achieve on the SDR-to-SDR communication links.

Thus, realizing all the concepts proposed in this paper in the porting process of legacy waveforms to SDRs becomes relevant when SDRs take the majority of radios being fielded in the same mission.

5. EXIT CHART ANALYSIS

In order to predict the convergence behavior of iterative processes like BICM-ID, a powerful method called *Extrinsic Information Transfer* (EXIT) chart has been proposed in [10]. In an EXIT chart, each constituent decoder is represented by a so-called EXIT curve. The subplots in Figure 4 show the EXIT curves for the rate $R_p=3/4$ resp. $R_p=9/20$ convolutional codes as well as the modulation schemes (as depicted in Figure 1) for an E_S/N_O = *7* dB. These curves specify bounds for a so-called *Decoding Trajectory* which illustrates the stepwise gains in *extrinsic information* achievable by the iterations.

It can be seen that only the new 32-QAM schemes offer the potential for gains in *extrinsic information* by the iterations. The decoding tunnel for the *Decoding Trajectory* is open for an E_S/N_O = *7* dB. No extra gains can be achieved for the original legacy system with the rate $R_p=3/4$ convolutional code and the 8-PSK modulation scheme with *Gray* labeling. Thus, the EXIT chart analysis confirms the BER behavior of the different schemes shown in Figure 3.

6. CONCLUSIONS

In this paper, we have analyzed if an added value can be provided to SDR operators in scenarios where interoperability to legacy systems is a must. For this purpose, we have applied the concepts of *Hierarchical Modulations* and *Incremental Redundancy* in the porting process of legacy waveforms to SDRs. The original legacy waveform is represented as the *base-layer* and the *enhancement-layer* carries some extra error protection information. We have shown by simulation that a higher error robustness (and with this, typically a longer communication range) can be realized by iterations.

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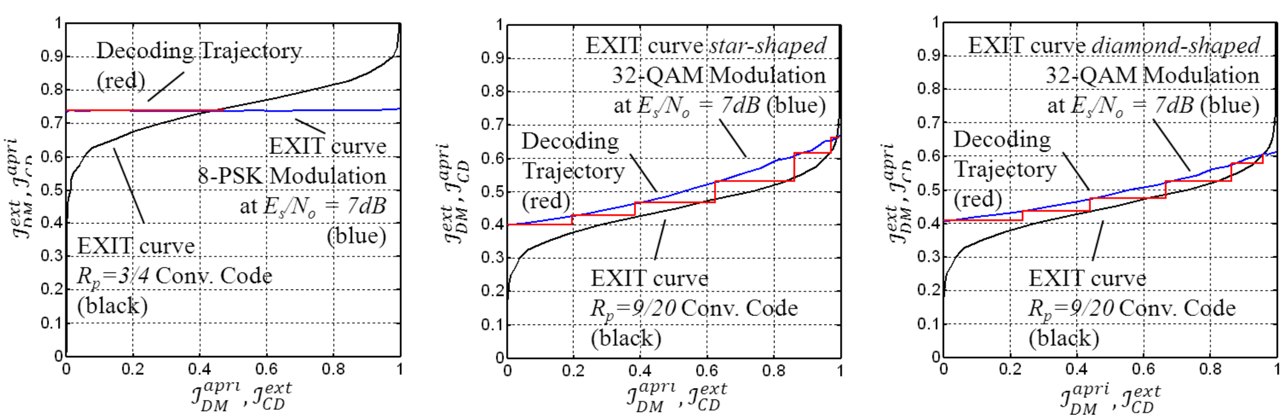

Figure 4: EXIT charts for the 8-PSK (left), *star-shaped* (center) and *diamond-shaped* 32-QAM schemes (right)