Design Space Exploration for Model-based Communication Systems

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***Abstract*—A main challenge of modem design lies in selecting a suitable combination of subsystems (e.g. ADCs/DACs, (de)modulators, scramblers, interleavers, and coding and filtering modules), each of which can be implemented in a multitude of ways. At the same time, the complete modem configuration needs to be tailored to the specific requirements of the intended communication channel or scenario. Therefore, *model-based* design methodologies have been popularized in this field, since their application facilitates the specification of individual modem components that are easily exchanged during the automated synthesization of the modem. However, this development has resulted in a tremendous increase in the number of synthesizable modem options. In fact, the optimal modem configuration for a communication scenario can not readily be determined, since an exhaustive analysis of all configuration possibilities is computationally intractable. As a remedy, we propose a fully automated Design Space Exploration (DSE) methodology for model-based modem design that combines the metaheuristic optimization of modem-configuration possibilities with an integrated simulative analysis of suitable communication-quality measures. The presented case study for an acoustic underwater communication scenario supports the described need for novel, automated methodologies in the area of model-based design, since the modem configurations discovered during a comparably short DSE are demonstrated to significantly outperform state-of-the-art modems from literature.**

***Index Terms*—design automation, model-based design**

I. Introduction

Communication modems typically need to perform several tasks to successfully transmit and receive signals over a communication channel. They, therefore, consist of a number of subsystems, or modules, ranging from Analog Digital Converters (ADCs)/Digital Analog Converters (DACs) to filtering, modulation, en- and decoding modules, etc. For each of these modules, a variety of implementation possibilities exists. The task of modem design consists of selecting a suitable combination and configuration of subsystems that enable successful communication over the channel, where the transmitted signals may be distorted by refraction, reflection, interference, or multi-path propagation effects—to name but a few disturbance factors that a modem should ideally be able to compensate. However, different modem configurations may exhibit significant performance differences in terms of communication quality depending on the conditions in the communication channel. This renders the problem of finding an optimal modem configuration non-trivial, especially with increasingly complex communication scenarios, as, e.g., in fast-changing environments such as underwater. Nowadays, many modems are still tailored to specific hardware and optimized manually using expert knowledge; furthermore, they are typically limited to specialized tasks and/or specific channel conditions [1], [2]. However, use cases such as prototypical modem design or design for custom communication scenarios require a more flexible development approach. As a remedy, model-based design methodologies allow for an easy specification and exchange of modem subsystems while offering the possibility to automatically synthesize the actual modem from the model-based specification [3]. The synthesized modems can be seamlessly evaluated using simulative or emulative techniques that include a model of the actual communication channel, since rapid prototyping and evaluations in the actual channel are often expensive and impracticable, as, e.g., for acoustic underwater communication (AUWC) that might require trials in tanks or even at sea.

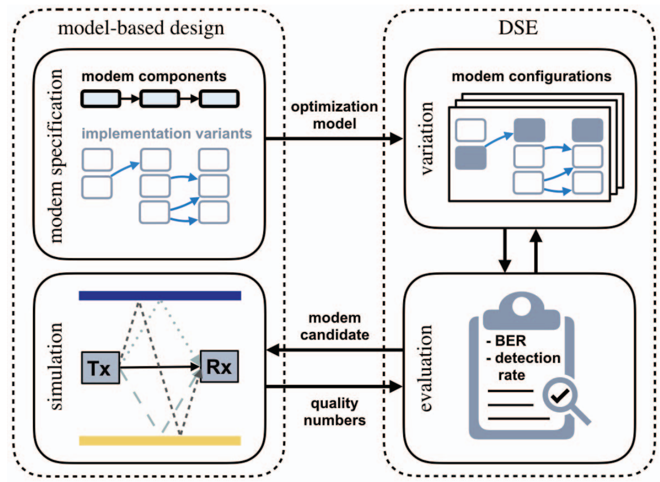

Fig. 1. Proposed DSE flow for model-based modem design.

While model-based design enables to significantly increase the number of available modem options, finding optimal modem configurations for a communication scenario becomes crucial. But, the sheer number of options can hardly be compared manually. At the same time, the complexity of real-world communication channels renders analytical predictions of a modem's performance computationally expensive if not impossible. An exhaustive *simulative* evaluation of all configuration possibilities is computationally intractable as well due to the significant execution time when simulating varying environmental conditions of the communication channel. Finally, the non-linearity of the communication-quality objectives combined with the fact that feasible modem configurations have to respect complex dependencies between modules requires the application of state-of-the-art hybrid optimization techniques [4].

Here, we propose a fully automated Design Space Exploration (DSE) methodology for model-based modem design that combines a metaheuristic exploration of modem-configuration possibilities with an integrated simulative analysis of suitable communication-quality measures, as illustrated in Fig. 1: The proposed DSE consists of (I) a graph-based optimization model that is automatically extracted from a model-based modem specification (top) and (II) is optimized using state-of-the-art optimization techniques (right). (III) The modems are evaluated w.r.t. a set of communication-quality objectives that are determined by (IV) synthesizing each modem candidate and simulating it using a realistic channel model (bottom).

In an exemplary case study, this work considers modem design for AUWC and illustrates the described need for novel methodologies in the area of model-based design. In particular, the modem configurations generated by a comparably short automatic DSE significantly outperform state-of-the-art modems from [3] w.r.t. detection rate, Bit Error Rate (BER), and other quality measures.

In the remainder of the paper, we discuss related work on model-based modem design and existing DSE methodologies in Sec. II. We propose an optimization model for model-based modem specifications in Sec. III as well as an automatic DSE flow with a detailed discussion of possible design constraints and the evaluation of optimization objectives in Sec. IV. The presented approach is validated in an experimental evaluation in Sec. V, before Sec. VI concludes the paper.

II. Related Work

Modem design is, as of now, mainly optimized manually and based on expert or domain knowledge [5]–[7]. Especially for AUWC as an exemplary use case, state-of-the-art modems are typically designed for specific channel conditions or communication scenarios [5], [8], since the acoustic underwater channel is subject to ever-changing environmental conditions that cause refraction, interference, or multi-path propagation effects that distort the communication signal and need to be compensated by the selected modem configuration. Since rapid prototyping and an experimental evaluation of modems in an actual underwater environment is, furthermore, expensive and impractical, model-based design methodologies have recently been popularized in this field [9]–[11]. Combined with increasingly sophisticated channel modeling techniques that include position- and distance-dependent as well as time-variant conditions of the environment [12], [13], a simulative evaluation of modem configurations becomes possible.

However, with increasing modem configuration options and time-consuming evaluation techniques comes the need for automated optimization. While DSE methodologies have been

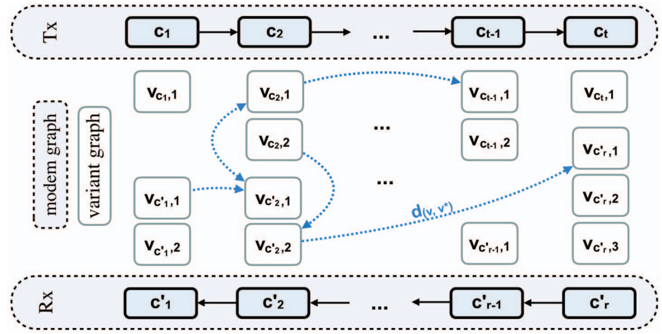

Fig. 2. Optimization model with *modem graph* $G_M(C, E_C)$ (top and bottom) and *variant graph* $G_V(V, D)$ (middle).

applied to selected areas of model-based embedded systems design, e.g. application mapping to Multiprocessor System-on-Chips (MPSoCs) [14] or the optimization of automotive power distribution systems [15], we are—to the best of our knowledge—the first to present a fully automated DSE methodology for model-based modem design at the physical layer that includes a simulative evaluation of communication-quality objectives in a realistic channel model.

III. Optimization Model

This section presents a graph-based optimization model for model-based communication systems at a suitable level of abstraction for automatic exploration. The proposed model is capable of representing the *modem structure*, *implementation variants*, and potential *restrictions* on feasible variant combinations and can be extracted automatically from any model-based specification. This allows for a flexible optimization of modem configurations in the presence of hard constraints.

Definition 1 (Modem Graph): A model-based modem is represented as a directed graph $G_M(C, E_C)$. Each node $c \in C$ represents a *task* of the modem, i.e. a basic building block, or module, required for successful communication (e.g. encoders/decoders, modulators, converters, etc.). Each of these modules can be implemented by a set of concrete *variants*, as defined in the variant graph (see Def. 2). Modules are, therefore, placeholders defining the basic modem structure, i.e. the processing pipeline for the transmitted or received signal. The modem structure is instantiated by selecting interchangeable implementations for each module, so that requirements on communication quality and/or the communication channel can be taken into account during modem design. The concrete structure of the modem is specified by modem-graph edges $E_C \subseteq C \times C$. Typically, the modem graph consists of two subgraphs for the transmission (Tx) and receiving (Rx) of messages, respectively, as depicted in Fig. 2 (top and bottom).

Model-based design allows to specify several *implementations* for each module, that are interchangeable as long as they implement a common interface. Furthermore, it is also possible that *no* implementation needs to be selected for specific modules (e.g. *no* convolutional en-/decoders for conditions with few multi-path interferences and low ambient noise, or if high

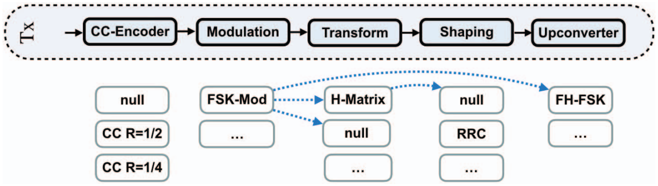

Fig. 3. Exemplary variant dependencies for FSK modulation.

good put is required). This is modeled using a dedicated *null*-variant. The set of variants, as well as potential dependencies between them, is specified in a *variant graph* G_V:

Definition 2 (Variant Graph): The directed variant graph $G_V(V, D)$ defines the set of concrete implementations, or variants, V that can be used to instantiate the individual modules in the modem graph. In particular, each module $c \in C$ can be implemented by at least one variant $v_{c,i} \in V$ ($i \in \mathbb{N}$), which may be the *null*-variant. Furthermore, *dependency* edges $D \subseteq V \times V$ are introduced to indicate if the selection of one variant entails the selection of another variant, i.e. a dependency edge $d_{(v_{c,i}, v_{c',i'})}$ represents the implication that if $v_{c,i}$ is selected for module c, then module c' is required to be instantiated by $v_{c',i'}$, as also illustrated in Fig. 2 (dotted arrows, middle). This is necessary, since the set of feasible variant combinations may be restricted if, e.g., a partial modem configuration is determined by the selected modulation scheme, or if only a certain combination of coding blocks is permissible.

Figure 3 illustrates possible variant dependencies for Frequency Shift Keying (FSK) modulation as an example of potential variant dependencies: Selecting the FSK variant restricts the set of valid variants in the Transform- and Upconverter-modules. In particular, if FSK modulation is selected, only the associated converter FH-FSK can be used, while H-Matrix or no transformation can be selected for the Transform-module. Additionally, selecting H-matrix transformation prohibits the applicability of signal shaping, indicated, again, using a dependency edge to the *null*-variant in this module.

Variant dependencies can, furthermore, be used to incorporate available domain knowledge about *preferable variant combinations* into the DSE. Both, module and variant vertices are annotated with *optimization parameters* that are optimized in addition to the modem configuration. In this work, we consider the permissible data length and the number of introduced redundancy bits, although other parameters, such as data accuracy, bandwidth, carrier frequency, or power consumption can easily be integrated in the proposed optimization model.

IV. DSE FOR COMMUNICATION SYSTEMS

Since model-based design allows for an easy specification of implementation variants, the design space of feasible modem configurations grows exponentially, i.e. the addition of a single variant doubles the number of possible modem configurations (barring any variant dependencies). Furthermore, the consideration of optimization parameters results in a multitude of modem candidates that form a design space whose size prohibits manual or exhaustive exploration. Combined with the fact that the simulative evaluation of modem configurations for realistic channel models is computationally expensive, DSE techniques incorporating efficient multi-objective optimization algorithms such as Multi-Objective Evolutionary Algorithms (MOEAs) are required in model-based modem design.

During DSE, concrete modem configurations are explored and optimized w.r.t. optimization objectives that capture a modem's performance in terms of communication quality. To this end, a suitable variant needs to be deployed, i.e. selected to instantiate each module $c \in C$ in the modem graph, so that the variant dependencies and other constraints on a feasible modem configuration are fulfilled. As is state-of-the-art in system-level DSE approaches, we propose to employ metaheuristic techniques to traverse the design space of modem configurations. This requires an encoding of the *search space* of possible modem configurations in a *genotype* that can efficiently be manipulated using standardized optimization operators.

A. Encoding Feasible Modem Configurations

Encodings for *constrained* optimization problems like DSE are typically not feasible by construction, i.e. the search space will contain infeasible genotypes that cannot directly be mapped to a solution in the design space. Hybrid optimization approaches use symbolic *repair strategies* that automatically correct any infeasible genotype to a feasible solution [16]. To this end, we formulate the domain-specific constraints on a feasible modem configuration as a 0-1-Integer Linear Program (ILP), where *binary variables* (highlighted **bold**) are introduced for all required elements of the optimization model.

For each module $c \in C$ in the modem graph, exactly one suitable variant $v_{c,i} \in V$ of the variant graph (including the *null*-variant) has to be selected for the resulting modem configuration. In the constraint set, a binary variable $\boldsymbol{v_{c,i}}$ indicates for every variant in G_V whether the corresponding variant implements the respective module ($\boldsymbol{v_{c,i}} = 1$) or not ($\boldsymbol{v_{c,i}} = 0$). Formally, this constraint is represented by:

$\forall c \in C:$
$$\sum_{v_{c,i} \in V} \boldsymbol{v_{c,i}} = 1 \tag{1}$$

Secondly, the potential dependencies between variants need to be respected: If a variant $v \in V$ is chosen that requires the selection of one (or more) other variants v', i.e. that has dependency edges $d_{(v,v')}$ in the variant graph, it has to be ensured that exactly one dependent variant v' is selected *per modem module* (indicated, again, using binary variables $\boldsymbol{d_{(v,v')}}$). In the running example from Fig. 3, this means that exactly one dependent variant has to be selected for the Transform-module and exactly one for Upconverter to fulfill all variant dependencies of the FSK-Mod variant. The corresponding constraint is defined as:

$\forall v_{c,i} \in V:$
$\quad \forall c' \in \{\tilde{c} | \tilde{c} \in C, \exists v_{\tilde{c},j} \in V : d_{(v_{c,i}, v_{\tilde{c},j})} \in D\}:$
$$\left(\sum_{v_{c',k} \in V:\ d_{(v_{c,i}, v_{c',k})} \in D} \boldsymbol{d_{(v_{c,i}, v_{c',k})}} \right) - \boldsymbol{v_{c,i}} = 0 \tag{2}$$

Finally, it has to be ensured that both variants, i.e. endpoints, of an activated dependency edge are also always selected to instantiate their respective variants. This is formalized as:

$\forall d_{(v_{c,i},v_{c',j})} \in D:$

$$\boldsymbol{v_{c,i}} - \boldsymbol{d_{(v_{c,i},v_{c',j})}} \geq 0 \tag{3a}$$

$$\boldsymbol{v_{c',j}} - \boldsymbol{d_{(v_{c,i},v_{c',j})}} \geq 0 \tag{3b}$$

Any *model* of this ILP, i.e. any variable assignment fulfilling constraints (1)–(3), represents a feasible modem configuration, as determined by the variants selected to instantiate the modem modules. The genetic representation, therefore, consists of a vector of all binary variant variables $\boldsymbol{v}_{c,i}$. During DSE, the variable assignments in the vector are varied to generate different modem configurations, while the constraint set ensures that infeasible combinations are automatically corrected. Further optimization variables, such as module- or variable-specific parameters or global parameters, such as payload or carrier frequency of transmitted messages, can additionally be included in the genetic encoding using integer or double variables restricted to feasible value ranges.

B. Simulative Evaluation of Optimization Objectives

During DSE, each modem configuration needs to be evaluated w.r.t. a number of optimization objectives that are used to determine the quality of each solution. This allows for a Pareto-ranking of the explored modems that is used to select the most promising modem candidates. We propose the automatic integration of (I) the synthesization of explored modem configurations in the model-based design flow with (II) a simulative or emulative evaluation of communication quality numbers in a realistic channel model. The simulative results are subsequently used to determine a modem's quality.

a) Optimization Objectives: We propose the following optimization objectives regarding communication quality:

Definition 3 (Detection Rate r_d (MAX)): r_d quantifies the fraction of received frames F_r vs. transmitted frames F_t, i.e.:

$$r_d = \frac{F_r}{F_t} \tag{4}$$

Note that this measure does not take into account whether the received frames could actually be successfully decoded or not. Instead, it indicates what fraction of transmitted frames could actually be *detected* by the Rx-configuration of the modem and were not missed due to noise, multi-path interferences, etc. in the communication channel. It is, therefore, an optimization objective that has to be maximized during DSE.

Definition 4 (Success Rate r_s (MAX)): The success rate r_s denotes the relative frequency of *received frames* F_r that could successfully be decoded, i.e. the inverse of the percentage of decoding errors F_{err}:

$$r_s = 1 - \frac{F_{\text{err}}}{F_r} \tag{5}$$

It serves as an indicator of how well the respective modem can tolerate distortions in the signal that might have occurred during transmission by, e.g., a suitable error-correction scheme[1].

Definition 5 (Bit Error Rate r_b (MIN)): The BER is a standard quality measure in communications engineering and quantifies the fraction of transmission errors on the level of bits. Specifically, it relates the number of bits distorted during transmission B_{err} to the number of bits received B_r:

$$r_b = \frac{B_{\text{err}}}{B_r} \tag{6}$$

Thus, BER is the only optimization objective to be minimized.

Definition 6 (Data Length l_p (MAX)): l_p measures the payload that can be transmitted by a specific modem configuration. A greater payload is obviously beneficial, since it allows more elaborate data transmission and communication during a mission—which might otherwise be limited to basic status signals or control messages. l_p is, therefore, maximized.

Optimizing the objectives from Def. 3–6 simultaneously allows to consider a variety of measures for communication quality during DSE. The proposed DSE flow, furthermore, allows an easy integration of further optimization objectives, if required, such as area, cost, energy consumption, etc.

b) Communication Channel Considerations: To determine the optimization objectives, we propose to use a simulative or emulative approach where the communication quality of each modem is evaluated using a realistic *channel model* of a specific communication scenario, i.e. a set of channel conditions that might occur during a mission. This is particularly necessary for AUWC, since the slow propagation speed of acoustic signals in water makes underwater communication much more susceptible to channel effects such as *multi-path propagation* or *refraction* of the acoustic signal on the ocean surface, seabed, or on boundaries between water layers of different temperatures or salinities [17]. To this end, the proposed DSE methodology automatically transforms each graph-based modem configuration from the optimization model back to a concrete model-based modem. An actual modem implementation can then be derived in the model-based approach and, e.g., compiled into HDL-code and synthesized on a Field-Programmable Gate Array (FPGA). The resulting implementation is then seamlessly connected to a simulation or emulation back end containing a suitable channel model, so that the performance of the modem—in terms of the optimization objectives defined above—can directly be observed and evaluated in the respective channel conditions.

In the proposed methodology, the evaluation back end can, however, be flexibly exchanged for use cases when, e.g., a purely analytical analysis or basic channel models such as Additive White Gaussian Noise (AWGN) are sufficient, as for, e.g., terrestrial communication scenarios [18].

[1] Note that the values for both r_d and r_s may exceed 1.00, since multi-path propagation effects in the channel may lead to the same frame being received and decoded more than once. This is, however, unproblematic, since it increases the chance of successfully decoding a frame.

V. Case Study

This section presents an experimental evaluation of the proposed DSE approach for AUWC. We give an overview of the underlying model-based modem specification, the channel model, and multi-objective optimization quality measures. Then, we compare optimization quality and the resulting Pareto front of modem configurations to a set of state-of-the-art reference modems from literature. A discussion of the advantages and drawbacks of DSE for AUWC concludes the case study.

A. Experimental Setup

The AUWC-DSE problem is modeled in the open-source framework OpenDSE [19] that utilizes the MOEA NSGA-II [20] in the optimization framework Opt4J [21] to optimize 4 optimization objectives r_d, r_s, r_b, and l_p (see Sec. IV-B). For the experimental evaluation, we compare the resulting Pareto-optimal modem configurations from the presented DSE approach to 6 hand-crafted modems from literature [3]—the current state-of-the-art methodology in the field of AUWC.

a) Modem model: The model-based modem is defined in Matlab/Simulink and consists of 24 modules for ADCs, DACs, (de)modulation, (de)scrambling, encoding, decoding, etc. Furthermore, it contains 47 variants with 30 dependencies, resulting in a total of $124,416$ possible modem configurations.

b) Simulative Evaluation: To evaluate each modem's communication quality, we employ a simulation using the sound speed profile of the specific channel conditions in Trond Fjord [13] as an exemplary case study. This channel model includes modifiable parameters such as wind speed, water temperature and salinity, the distance and depth position of communicating modems, as well as a detailed model of the ocean surface and the seabed. To optimize for a modem configuration that performs well across various channel conditions in the fjord, we average the optimization objectives of each modem over 4 simulation runs for *extreme* channel conditions that may be encountered in the fjord: We vary the *communication distance* between sender and receiver and the *wind speed*, since they are two of the main parameters affecting communication quality. The presented methodology is, however, just as well applicable to different or a greater variety of channel conditions, so that separate optimization runs for specific communication scenarios, geographic locations and/or mission types are conceivable. Furthermore, the simulation of each modem configuration is set to 20 frames (with a payload of $80 - 2,024$ bits each) in each channel condition.

B. DSE Evaluation

The presented DSE results are the average over 3 DSE runs, starting with randomly generated populations of modem configurations (population size: 100) with 25 newly generated solutions per iteration and an exploration time of 50 iterations.

a) Optimization Quality: Multi-objective optimization quality is evaluated by established measures *ϵ-dominance* and *hypervolume* [22]. *ϵ-dominance* quantifies the normalized distance between the Pareto front resulting from one approach and the Pareto front of globally optimal solutions across all approaches. *hypervolume* compares the deviation of the volumes covered by one approach and the globally optimal solutions in the multi-dimensional objective space. For both measures, smaller values ($\rightarrow 0$) correspond to *higher* optimization quality.

Table I depicts optimization quality between the reference modems *ref* [3] and the modems optimized by the proposed DSE flow *DSE*. The optimized modems *DSE* are shown to significantly outperform *ref* [3] for both quality measures. In particular, optimization quality is improved by $\approx 65 - 69\%$, with comparably low standard deviations of $9 - 13\%$ between optimization runs. Column *coverage* depicts the percentage of Pareto-optimal solutions discovered by one approach relative to the other. *DSE* discovered 100% of the hand-crafted Pareto-optimal modems during the automatic optimization (starting from randomly generated modem configurations), while *ref [3]* contains none of the *DSE* modems. This means, that the *overall* Pareto-optimal modems are all from *DSE*, further highlighting the potential of DSE over expert knowledge-based design.

To verify these results, we performed a more elaborate evaluation of the Pareto-optimal modems of both approaches with an increased transmission of 50 frames per channel. The verification approaches *-ver.* confirm the described results, with even improved optimization quality numbers for *DSE* modems.

b) Pareto fronts: Figure 4 compares the modems resulting from *DSE* to *ref* [3] in the objective space for 3 of the 4 optimization objectives (r_d, r_s, and r_b) (arrows indicate the optimal values of each objective). From the 6 hand-crafted modems, only 3 are actually part of the resulting Pareto-front for the explored channel model, which was not readily evident to the expert designers. The proposed DSE methodology, on the other hand, is able to detect and exclude such *dominated* modem configurations early on during the optimization automatically. Secondly, DSE results in a great number and variety of non-dominated modem configurations, so that a more informed selection between modems of different communication qualities can be made for the final modem implementation. In View A, the optimal modem configurations with high r_d, r_s and low r_b are located in the front top left corner, where clearly more of the *DSE* modems are situated. In particular, the explored modems have a significantly improved detection rate r_d. Furthermore, View B shows that DSE results in modem configurations with reduced BERs, confirming that *DSE* modems provide better communication quality than the hand-tailored modems. While

TABLE I
Optimization quality in ϵ-dominance and hypervolume (average and standard deviation), and coverage between reference modems and DSE, as well as verified modems.

quality measure	ϵ-dom.		hypervolume		coverage
approach	avg.	std. dev.	average	std. dev.	
ref [3]	0.81	0.00	0.98	0.00	0.00
DSE	**0.26**	0.09	**0.30**	0.13	**1.00**
ref-ver. [3]	0.82	0.00	1.19	0.00	0.00
DSE-ver.	**0.00**	0.00	**0.00**	0.00	**1.00**

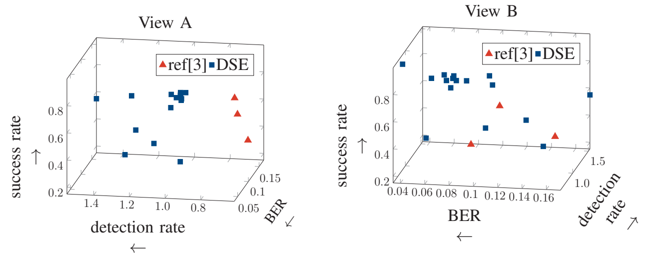

Fig. 4. Comparison between the resulting Pareto-fronts of reference modems and DSE from two perspectives (View A, B).

both approaches result in modems with success rates ranging from $\approx 40\% - 80\%$, the proposed DSE yields a greater number of modems at the higher end of the spectrum (up to $r_s \approx 93\%$).

C. DSE time

While the resulting communication-quality indicators clearly recommend DSE-based modem design, the simulative evaluation of each modem is a bottleneck in terms of exploration time. With an evaluation time of ≈ 8 minutes per explored modem, the execution time of the complete optimization stack of just a few milliseconds per modem becomes de facto negligible. Running in single-thread configuration on a desktop machine, one DSE run as presented here took about 7 days. But, since the metaheuristic optimization approach is embarrassingly parallel, i.e. each modem can be evaluated in parallel, using multi-threading on many-core computers reduces the overall DSE time tremendously with close to linear speed-up. Furthermore, utilizing different evaluation back ends such as hardware-accelerated emulation can reduce the evaluation time itself.

VI. Conclusion

This work presents a fully automated DSE methodology for state-of-the-art model-based design approaches as, e.g., used in modem design for AUWC. It proposes (I) a graph-based optimization model that is automatically extracted from a model-based specification (II) to be explored using hybrid metaheuristic optimization techniques. The DSE flow incorporates (III) the automatic synthesization of modem configurations for (IV) an integrated simulative analysis of communication-quality measures, ranging from the BER to the rates of successfully received and decoded messages. The presented case study supports the described need for novel design methodologies in the field of model-based design, since the modem configurations resulting from a comparably short DSE are demonstrated to significantly outperform modem configurations that were created based on expert and domain-specific knowledge—the current state-of-the-art in this field.

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