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To cite this version:
Adrien Cassagne, Olivier Hartmann, Mathieu Leonardon, Kun He, Camille Leroux, et al.. AFF3CT: A Fast Forward Error Correction Toolbox!. SoftwareX, 2019, 10, pp.100345. 10.1016/j.softx.2019.100345. hal-02358306
AFF3CT: A Fast Forward Error Correction Toolbox!

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ARTICLE INFO

Article history:
Received 18 February 2019
Received in revised form 5 August 2019
Accepted 15 October 2019

Keywords:
Communication chain
Channel coding
Monte Carlo simulation
Forward error correction library
Digital modulation
Reproducible science
Multi-node
Multi-thread
Vectorization

ABSTRACT

AFF3CT is an open source toolbox dedicated to Forward Error Correction (FEC or channel coding). It supports a broad range of codes: from widespread turbo codes and Low-Density Parity-Check (LDPC) codes to more recent polar codes. The toolbox is written in C++ and can be used either as a simulator to quickly evaluate algorithms characteristics, or as a library in Software Defined Radio (SDR) systems or for other specific needs. Most of the decoding algorithm implementations aim at low latency and high throughput, targeting multiple Gb/s on modern CPUs. This is crucial in both simulation and SDR use cases: Monte Carlo simulations require high performance implementation as they commonly target the estimation of approximately $10^{12}$ bits. On the other hand, the implementations in real systems have to be very efficient to be competitive against dedicated hardware ones. Finally, AFF3CT emphasizes the reproducibility of state-of-the-art results by providing public references and open, modular source code.

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1. Motivation and significance

It is now commonplace to state that Humanity has entered the era of communication. Moreover, all kinds of objects will increasingly also use communication technology, to exchange information in the Internet of Things (IoT). Despite their variety, all communication systems are based on a common abstract model proposed by Claude Shannon. In his seminal paper [1], he proposed to model a communication system with five components: an information source, a transmitter, a channel, a receiver and a destination. This model was later refined as shown in Fig. 1. The source produces a digital message to be transmitted. The channel encoder transforms it to make it less prone to errors.

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https://doi.org/10.1016/j.softx.2019.100345
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Table 1

| Name           | Contributors | Lines | Commit First | License | Polar | LDPC | Turbo | Turbo P. | BCH | RS | Conv. | RA | Rep. | Erasure |
|----------------|--------------|-------|--------------|---------|-------|------|-------|----------|-----|----|-------|----|------|---------|
| AFF3CT         | 11           | 76k   | 2016         | MIT     | ✓     | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| eccpage        | 20           | –     | 1989         | 2006    | ✓     | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| EZPVID         | 2            | 6k    | 2014         | 2018    | GPLv3 | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| FastECC        | 2            | 1k    | 2015         | 2017    | Apache 2.0 | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| FEC-AL         | 1            | 3k    | 2018         | 2018    | BSD 3-Clause | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| FECpp          | 2            | 2k    | 2009         | 2019    | –     | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| GNURadio       | 205          | 270k  | 2006         | 2019    | GPLv3 | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| IT++           | 109k         | 2003  | 2018         | GPLv3   | ✓     | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| LDPC-codes     | 5k           | 2012  | 2012         | Copyright | ✓    | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| LeGal          | 1            | 83k   | 2015         | 2019    | –     | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| Leopard        | 4            | 5k    | 2017         | 2018    | BSD 3-Clause | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| libcorrect     | 6            | 5k    | 2016         | 2018    | BSD 3-Clause | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| OpenAir        | 148          | 740k  | 2013         | 2019    | OAI Public | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| OpenFEC        | 8            | 55k   | 2009         | 2014    | Cecil-C | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| Schifra        | 1            | 7k    | 2010         | 2018    | GPLv3 | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| Siamese        | 1            | 11k   | 2018         | 2019    | BSD 3-Clause | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| Tavildar-Polar | 1            | 2k    | 2016         | 2017    | –     | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| Tavildar-LDPC  | 1            | 1k    | 2016         | 2016    | –     | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| the-art-of-ec  | 1            | –     | 2006         | 2009    | Copyright | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |
| TurboFEC       | 3            | 4k    | 2015         | 2018    | GPLv3 | ✓    | ✓     | ✓        | ✓   | ✓  | ✓     | ✓  | ✓   | ✓       |

The performance of this chain is measured by estimating the residual error rate at the sink. This rate is directly driven by the choice of the channel encoder and decoder. After Shannon, researchers have designed new coding/decoding schemes to approach Shannon’s theoretical limit ever closer. Indeed, recent progresses managed to design practical codings performing very close to that limit, and already integrated in everyday communication systems.

On the eve of the 5G mobile communication generation, the challenge is now to design communication systems able to transmit huge amounts of data in a short time, at a small energy cost, in a wide variety of environments. Researchers work at refining existing coding schemes further, to get low residual error rates with fast, flexible, low complexity decoders.

The table presents, to the best of our knowledge, a list of currently available C/C++ open source channel coding simulators/libraries. Note that this table is frequently updated on the AFF3CT website. 1 We choose to compare with projects compiled as binaries, since they aim at high throughput and low latency, as AFF3CT. Many open source projects in Python or in MATLAB exist as well, but these tools are usually slower than compiled binaries, and rather aim at prototyping.

1 C/C++ Open Source FEC Libraries: https://aff3ct.github.io/fec_libraries.html.
Fig. 3. AFF3CT simulation of various code families.

Table 1 shows that, generally, the C/C++ FEC libraries target a single family or a small subset of channel codes. As a consequence, a large effort is spent to re-develop similar features, since all those libraries and tools share many characteristics (except the channel code itself). AFF3CT attempts to lower this redundancy by releasing a full simulator/library that consistently supports a wide range of channel codes to the community. AFF3CT also tries to homogenize usage (command line, C++ interfaces, etc.) for all code families. Table 1 does not aim at comparing channel code implementation performances. Instead, on the AFF3CT website, an overview of software channel decoders state-of-the-art is provided for turbo, LDPC and polar codes.

3. Software description

AFF3CT is a Forward Error Correction (FEC) toolbox. The most important tools it includes are the simulator and the library. Additionally, the toolbox comes with a bank of simulated references, a GUI software to browse those references, and a set of predefined configuration files for common communication standards.

3.1. Simulator

As a standalone simulator, AFF3CT proposes to simulate various communication chains with a broad range of codes. The simulator is a command line program; Fig. 2 depicts its main arguments: -m and -M set the minimum and the maximum Signal Noise Ratio (SNR, $E_b/N_0$) to simulate, -s specifies the iteration step inbetween. Parameter -C selects the channel code type, -K sets the length in bits of the initial information message and -N sets the codeword size, which is the encoder output size. The command line interface is designed to be easily used from scripts. Fig. 3 shows simulations ran with AFF3CT on various code types (BPSK modulation and AWGN channel).

3.2. Library

As a FEC library, AFF3CT can be used programmatically, for instance in Software Defined Radio (SDR) contexts or in simulations. AFF3CT blocks can be used in external projects without restriction. Compute intensive blocks are optimized and vectorized to run fast on a single core. The library is thread-safe; however, it is not multi-threaded by itself, in contrast to the simulator. Instead, it is the responsibility of the user to manage multi-threading.

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2 FEC Software Decoders Hall of Fame: http://aff3ct.github.io/hof_turbo.html.

3 The AFF3CT simulator comes with more options, omitted here for concision.
The codecs naturally encompass the encoders and decoders, but they can also include puncturing patterns to shorten frames length according to some communication standards. Most of the codec algorithms come from the literature, while the others have been designed under AFF3CT [2–5]. In channel coding, the decoder is the most time-consuming process, compared to the puncturing and the encoding processes. This is why a specific effort is put on ensuring the high computing performance of the decoders. Most of the decoding algorithms have thus been optimized to satisfy high throughput and low latency constraints [6–9]. Those optimizations generally involve a vectorized implementation, a tailored data quantization and the use of fixed-point arithmetic.

In typical communication chains, it is necessary to adapt the digital signal to the physical support. This operation is performed by the modulator and conversely by the demodulator. AFF3CT comes with a rich set of modems to this purpose. Table 3 lists all the supported modems. AFF3CT supports several coded modulation/demodulation schemes like the Continuous Phase Modulation (CPM) [10,11] and the Sparse Code Multiple Access (SCMA) modulation [12–14] (many codebooks are supported [15–21]). It allows to easily combine and evaluate the channel codes with several types of modulations. In the case of the CPM, analogical wave shapes are also simulated. The other modulation schemes are at the digital level.

For simulation purposes, it is crucial to emulate the behavior of the physical layer. This is the role of the channel. There are many possible configurations depending on the physics phenomena to simulate. Table 4 reports all the supported channels.

The channels involve complex floating-point computations. It is frequent to use exponential and trigonometric operations. Those types of operations cost a large amount of CPU cycles to be computed. As for the decoders, the channels have been carefully optimized based on branch instructions reduction and massive vectorization.
Table 5
Specifications of the target processors.

| CPU          | SIMD instr. | Name           | Size  | per Proc. | # Proc. | # Cores per Proc. | Freq. (GHz) | SMT | Turbo Boost |
|--------------|--------------|----------------|-------|-----------|---------|--------------------|-------------|-----|-------------|
| ARM          | NEON         | ThunderX2 CN9975 | 128-bit | 2         | 28      | 2.00               | ✓           |     |             |
| Intel        | AVX-512F     | Xeon Phi 7230   | 512-bit | 1         | 64      | 1.30               | ✓           |     |             |
| Intel        | AVX2         | Xeon E5-2680 v3 | 256-bit | 2         | 12      | 2.50               | ✓           |     |             |
| Intel        | AVX-512BW    | Xeon Gold 6140  | 512-bit | 2         | 18      | 2.30               | ✓           |     |             |
| Intel        | AVX-512BW    | Xeon Gold 6142  | 512-bit | 2         | 16      | 2.60               | ✓           |     |             |

Table 6
AFF3CT multi-node speedups (single node: 2 × Xeon E5-2680 v3).

| Nodes | Cores | Info. T/P (Mb/s) | Speedup |
|-------|-------|------------------|---------|
| 1     | 24    | 1950             | 1.00    |
| 2     | 48    | 3901             | 1.95    |
| 4     | 96    | 7793             | 4.00    |
| 8     | 192   | 15829            | 8.12    |
| 16    | 384   | 31640            | 16.22   |
| 32    | 768   | 63075            | 32.34   |

Fig. 5. AFF3CT simulation of a (2048,1723) Polar code, FA-SCL decoder. $L = 32$, BPSK modulation, AWGN channel, $E_b/N_0 = 4.5$ dB (BER = $4.34 \times 10^{-10}$, FER = $5.17 \times 10^{-8}$).

All these features are available from the simulator and in the library. Many additional functional functionalities available are skipped here for concision.

3.5. Software Continuous Integration

AFF3CT’s development leverages streamlined Continuous Integration (CI) process. Each new commit to the version control repository triggers a comprehensive sequence of tests to catch potential regressions. Regression tests are based on past simulation results, validated from the state-of-the-art.

The CI process enables us to safely and confidently integrate contributed features and improvements from the community to AFF3CT. It also helps to keep the code review time by the core development team low-enough to swiftly integrate such contributions into the master branch.

4. Illustrative examples

4.1. Using AFF3CT as a simulator

Fig. 5a depicts the speedups achieved on various modern CPU architectures detailed in Table 5, while Fig. 5b exposes the corresponding simulation information throughputs. In Fig. 5a, the speedups on each architecture are computed with respect to the single thread simulation time on the same architecture. Each run assigns at most one AFF3CT thread to each hardware thread, thus, since the architectures have different number of hardware threads, the presented speedups do not all have the same number of measurement points. In Fig. 5, an $N = 2048$ and $K = 1723$ Polar code (FA-SCL decoder, $L = 32$, 32-bit GZip 0x04C11DB7 CRC) is simulated with a BPSK modulation and over an AWGN channel ($E_b/N_0 = 4.5$ dB, last SNR point of the blue curve in Fig. 3a). The frozen bits of the polar code have been generated with the Gaussian Approximation method (GA) [22]. The communication chain is fully vectorized with the MIPP wrapper [23] and multi-threaded with C++11 threads. The vectorization is applied at the tasks level (cf. Section 3.3) to take advantage of the algorithms intrinsic level of parallelism, when the multi-threaded parallelism is used, to reduce the simulation time by multiplexing the number of concurrent communication chains, thanks to the independence property of Monte Carlo simulations. In order to achieve highest possible throughputs, the receiver part of the simulator is configured to work with 8-bit fixed-point representation for real numbers. It has been shown that this representation does not degrade the decoding performances of the FA-SCL decoder [5]. However AFF3CT algorithms implementations can also be run on other representations like 64/32-bit floating-point and 16-bit fixed-point. For all the CPU targets, the code has been compiled with the C++ GNU compiler version 8.2.0 on Linux, with the following optimization flags: -O3 -funroll-loops -march=native. Note that AFF3CT also works on Windows and macOS at the same level of performance.

The simulations scales rather well on the tested architectures. The data remains in the CPU caches because of the moderate frame size ($N = 2048$). Scaling on the Xeon Gold 6142 is not as good as the other targets, because the Intel Turbo Boost technology is enabled on this platform: the CPU runs at higher frequencies when the number of active cores is low. AFF3CT effectively leverages the simultaneous multi-threading (SMT) technology. This is especially true for the ThunderX2 CN9975 and Xeon Gold 6140 targets. The SMT technology helps to improve the usage of the available instruction-level parallelism.

Table 6 shows the multi-node scaling with the OpenMPI library (version 3.1.2). The information throughput (T/P) and the speedup are almost linear with the number of nodes: This is
expected because there are very few communications between the various MPI processes. Note that the super-linear scaling is due to the measurements imprecision.

Those aforementioned results demonstrate the high throughput capabilities of AFF3CT. For instance, when using 32 MPI nodes on the given (2048,1723) polar code, it takes about one minute to estimate the $E_b/N_0 = 4.5$ dB SNR point (BER $= 4.34e−10$, FER $= 5.17e−08$).

### 4.2. Using AFF3CT as a library

Listing 2: Modules allocation.

```cpp
1 #include <aff3ct.hpp>
2 using namespace aff3ct;
3
4 // allocate the module objects
5 module::Source_random<> Src(K);
6 module::Encoder_repetition_sys<> Enc(K, N);
7 module::Modem_BPSK<> Mdm(N);
8 module::Channel_AWGN_LLR<> Chn(N);
9 module::Decoder_repetition_std<> Dec(K, N);
10 module::Monitor_BFER<> Mnt(K, E);```

In this section the communication chain proposed in Fig. 4 is implemented with the AFF3CT library. The first step is to allocate the modules. In Listing 2 we chose to allocate modules on the stack, but it is also possible to do the same on the heap. $K$ is the number of information bits, $N$ is the frame size and $E$ is the number of erroneous frames to simulate. One can notice that there is a module for the encoder and for the decoder, this differs from Fig. 4 where `encode` and `decode` are tasks of the codec module. In fact the codec module exists in AFF3CT and it is an aggregation of the encoder and decoder modules. For simplicity, we chose not to use the codec module here. In this basic example, a repetition code is selected, it simply repeats the information bits $N/K$ times.

The next step is to bind the sockets of successive tasks together (see Listing 1): The `source` module output socket module `::src::sck::generate::U_K` is connected to the input socket module `::enc::sck::encode::U_K` of the `encoder`, and so on, for all the sockets of the tasks.

Listing 3: Tasks execution.

```cpp
1 // the simulation loop
2 while (!monitor.fe_limit_achieved()) {
3  Src(module::src::tsk::generate).exec();
4  Enc(module::enc::tsk::encode).exec();
5  Mdm(module::mdm::tsk::modulate).exec();
6  Chn(module::chn::tsk::add_noise).exec();
7  Mdm(module::mdm::tsk::demodulate).exec();
8  Dec(module::dec::tsk::decode_siho).exec();
9  Mnt(module::mnt::tsk::check_errors).exec();
10 }
```

The simulation is then started and each task is executed. In Listing 3, the whole communication chain is executed multiple times, until the $E$ frame error limit is achieved (typically $E = 100$ erroneous frames).

To propose an easy to use interface, sockets and tasks can be selected through the [] operator, which takes a C++ strongly typed enumerate. This way it is possible to specialize the code depending on whether it is a socket or a task. Strongly typed enumerates are checked at compile time (contrary to standard enumerates), making it impossible to use wrong values.

### 5. Impact

AFF3CT is currently used in several industrial contexts for simulation purposes (Turbo concept, Airbus, Thales, Huawei) and for specific developments (CNES, Schlumberger, Airbus, Thales, Orange), as well as in academic projects (NAND French National Agency project, IdEx CPU). The MIT license used in the project is very permissive and gives confidence to industrial and academic partners, who can then invest themselves and reuse parts of AFF3CT in their own projects without any restrictions.

An important aspect of channel coding is the ability to reproduce state-of-the-art results, because there are many possible configurations and it is time-consuming to rediscover those configurations. This is why AFF3CT comes with a large database of pre-simulated performance curves with all the required parameters. Some research projects have been using AFF3CT as a Ref. [24–30]. All pre-computed simulation results are available at a glance on the online comparator, with corresponding command lines to reproduce them. Combined with the possibility to download AFF3CT last builds, testing the reference configurations, replicating the experiments and playing with parameters is straightforward. AFF3CT aims to achieve results easily reproducible by the scientific community.

It comes with a comprehensive documentation, to help using, modifying, extending existing coding schemes, to potentially improve them or to adapt to other domains. Moreover, AFF3CT can be used to prototype and evaluate hardware implementations [31].

### 6. Conclusion and future works

In this paper we presented AFF3CT, a forward error correction toolbox that enables high throughput simulations thanks to multi-node, multi-threaded and vectorization paradigms. AFF3CT makes reproducible and replicable science possible with a large database of reference simulations available, and tools to reproduce them quickly on commonly used systems. Both the AFF3CT library and standalone simulator ship with a wide range of heterogeneous algorithms, and can easily be enriched by the community, for instance with additional families of codes, or to fit new application contexts such as software defined radio.

In the near future, a wrapper is scheduled to directly use the AFF3CT library from MATLAB and Python. It will give the opportunity to non-experts in C++ community to easily take
advantage of the high speed implementations available in the toolbox. On the other hand, we plan to extend the range of the project with synchronization modules: this will enable full SDR emitter and receiver using the AFF3CT library.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study has been carried out with financial support from French State, managed by the French National Research Agency (ANR) in Programme IdEx Bordeaux CPU (ANR-10-IDEX-03-02) and in Project NAND, France (ANR-15-C52-0006-01). Experiments were conducted on the PlaFRIM platform.

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