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BMD: A COMPREHENSIVE FRAMEWORK FOR MULTI-MODAL BIOMETRIC DATA

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1 Introduction

This document describes a comprehensive framework for the management of biometric data, developed as part of the COBS4FUN project.

COBS4FUN stands for "Compression Of Biometric Signals for FUture Networks applications" and was a cascade call project of the structural project S7 FUN-Media, coordinated by the Politecnico di Torino (Spoke 4) and funded by the European Union – NextGenerationEU as part of the NRRP – M4C2, Investment 1.3, program "RESearch and innovation on future Telecommunications systems and networks, to make Italy more smART" (RESTART), PE00000001.

The main aim of COBS4FUN was the development of new formats and compression techniques for efficient encoding and transmission of biometric signals.

In particular, a comprehensive framework has been developed for the management of biometric data, with a focus on interoperability, modularity, and efficient storage and transmission.

The framework includes:

- a new standardized format for biometric multimodal data (**BMD**),
- a dedicated tool for its creation and manipulation (**BMDComposer**), and
- a flexible environment for the development and evaluation of compression algorithms for biometric signals and traits (**COBS** - Compression Of Biometric Signals and traits).

This document focuses specifically on the **BMD** format and the related **BMDComposer** tool, specifically developed for the creation and management of BMD-compliant data archives.

2 The BMD Framework

2.1 Why a New Data Format

The management of biometric multimodal data presents significant challenges in contemporary research and clinical practice. Current approaches typically involve separate storage and handling of waveform recordings, images, metadata, and annotations, leading to fragmented datasets that compromise data integrity and research reproducibility. Existing formats lack integrated privacy-preserving measures required for sensitive personal data, while the absence of standardized compression and annotation systems creates interoperability barriers across different research platforms and clinical environments.

Moreover, traditional biometrics data workflows suffer from several critical limitations. Recordings from wearable biometric and biomedical devices are often stored as raw files without embedded metadata, making it difficult to trace acquisition parameters or patient information. These require separate annotation tools that cannot seamlessly integrate with corresponding recordings or temporal measurements. Furthermore, privacy regulations in healthcare demand robust encryption mechanisms that current formats do not natively support.

The research community has long recognized the need for a unified format that can encapsulate heterogeneous biometrics data, i.e., signals and images representing various biometric traits, while maintaining security, ensuring traceability, and supporting advanced analysis workflows. The absence of such a standard has resulted in proprietary solutions that sometimes lock research data into vendor-specific ecosystems, hindering collaborative research and long-term data accessibility.

To address these limitations, we developed a new data format - Biometric Multimodal Data (BMD) - specifically designed to bridge this gap. BMD provides a standardized, extensible, and secure framework for storing and sharing biometric data across different modalities and research scenarios. It promotes interoperability, ensures data traceability, and facilitates the integration of biometric datasets into advanced analysis workflows.

2.2 The BMD Format: Innovation and Technical Advantages

The Biometric Multimodal Data (BMD) format addresses these fundamental challenges through a comprehensive technical approach that unifies multimedia content, metadata, security, and compression capabilities within a single container. The format employs a structured JSON header coupled with binary data blocks, enabling efficient storage and retrieval while maintaining human-readable metadata accessibility.

Security represents a core innovation of the BMD format through its integrated cryptographic framework. Personal and sensitive data undergo AES-256 encryption using automatically generated keys, ensuring compliance with healthcare privacy regulations such as HIPAA and GDPR. The format additionally implements RSA-2048 digital signatures for data integrity verification, allowing researchers to authenticate the provenance and completeness of datasets throughout their lifecycle. This dual-layer security approach operates transparently, requiring no additional steps from end users while providing enterprise-grade protection for sensitive biometric information.

Scalability considerations address the realities of modern research, where datasets frequently exceed gigabyte scales. With this aim, the BMD format introduces advanced compression capabilities specifically designed for biometric data characteristics. Unlike other biomedical formats, BMD supports domain-specific codec configurations that can be customized for different acquisition modalities. The system accommodates both lossless and lossy compression algorithms, with automatic selection based on data type and research requirements. Custom codec libraries can be embedded within BMD files, ensuring long-term accessibility even when proprietary compression algorithms are used.

The annotation system within BMD provides unprecedented flexibility for biometric research applications. Temporal annotations enable precise marking of signals with sample-accurate positioning, while spatial annotations support rectangular region marking on images representing biometric traits such as fingerprints and iris. The format supports multiple annotation targets, allowing researchers to annotate entire files, individual channels, or channel groups depending on their analytical needs. The format natively handles 32, or higher channel configurations with individual channel labeling and grouping capabilities. This eliminates the need for complex post-processing workflows to manage multi-channel datasets and enables sophisticated visualization and analysis directly from the source format.

The format's design philosophy emphasizes interoperability without sacrificing functionality. BMD files can be processed by generic tools for basic access while providing rich API interfaces for specialized biometric applications. This dual accessibility ensures that research data remains usable across different software environments and can survive changes in research infrastructure over time.

The BMD format employs efficient indexing mechanisms and supports selective loading of data components, enabling researchers to work with large datasets without excessive memory requirements. The format's modular structure allows for distributed processing workflows where different components can be analyzed independently while maintaining data consistency and traceability. The BMD file format employs a layered architecture consisting of four sequential components: a fixed-size header length field, a variable-length JSON metadata header, concatenated binary data blocks, and an optional digital signature (see Fig. 1). This structure enables efficient random access to metadata while maintaining compatibility with streaming parsing implementations.

The file begins with a 4-byte unsigned integer encoded in little-endian format specifying the byte length of the subsequent JSON header. This fixed-size prefix allows parsers to determine header boundaries without scanning the entire file. Following the header size field, the JSON-encoded metadata section contains complete information about file structure, compression configurations, security

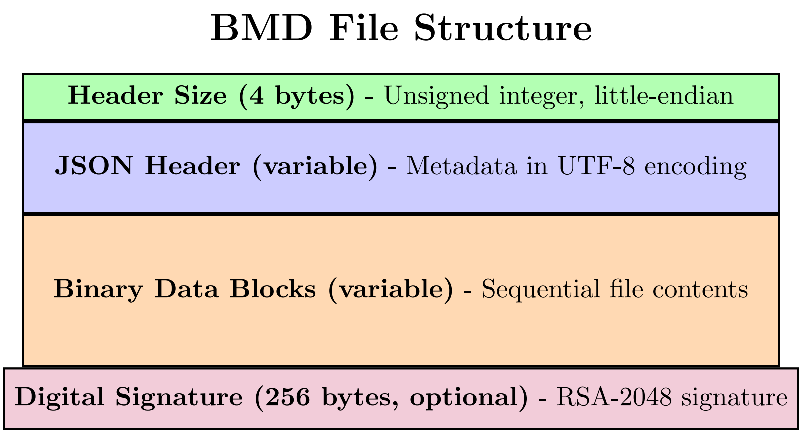

Figure 1: Physical organization of a BMD file showing the four sequential components.

parameters, and annotations.

In particular, the JSON header employs a hierarchical structure organized into eight primary sections: version identification, personal information, acquisition parameters, general notes, signal definitions, image definitions, annotations, compression configuration, security metadata, and channel configurations. Each section serves a distinct functional purpose while maintaining referential integrity through consistent identifier schemes.

The binary data section immediately follows the header, containing raw or compressed file contents organized as sequential blocks indexed by the header.

Binary data organization follows an offset-based indexing scheme where each file entry in the header specifies its location within the binary section through "offset" and "size" fields. This approach enables selective file extraction without loading the entire binary payload into memory, supporting efficient processing of large-scale biometric datasets. The MD5 checksum accompanying each file entry provides content verification capabilities, detecting corruption or tampering during transmission or storage.

When digital signatures are enabled, an RSA-2048 signature of fixed length terminates the file, covering both header and binary data for integrity verification.

The complete BMD format specification is reported in Deliverable 3.2 entitled *"BMD: A New Data Exchange Format for Biometric Signals and Traits"*.

Table 1 summarizes the key technical features that distinguish BMD from existing biometric data formats, highlighting innovations in multimodal integration, security, compression, and metadata management.

Table 1: Key features and technical advantages of the BMD format.

Feature	Technical Advantage
Multimodal	Unified container for heterogeneous biometric data including electrophysiological signals (ECG, EMG, EEG) and biometric trait images (fingerprints, iris, face) within a single file.
Security & Privacy	Integrated AES-256 encryption for sensitive personal data and RSA-2048 digital signatures for integrity verifications.
Data Integrity	MD5 checksums for each file component combined with optional RSA digital signatures provide cryptographic verification of data authenticity and detect corruption during transmission or storage.
Interoperability	Human-readable JSON metadata combined with standard binary encodings enable processing by generic tools while providing rich APIs for specialized biometric applications.
Comprehensive Metadata Management	Structured JSON header with flexible key-value pairs for personal information, acquisition parameters, and research-specific annotations, maintaining complete dataset provenance.
Multi-modal and Multi-level Annotations	Sample-accurate temporal annotations for signals and pixel-precise spatial annotations for images, with multi-target support for entire files, individual channels, or channel groups.
Multi-Channel Support	Native handling 32 or higher channel configurations with individual channel calibration (physical units, scaling factors), logical grouping, and coordinated visualization capabilities.
Advanced Compression	Support for compression algorithms with custom codec library embedding, enabling both lossless and lossy compression optimized for biometric data characteristics.
Scalability	Offset-based binary indexing enables selective file extraction and streaming access without loading entire datasets into memory.
Extensibility & Versioning	Modular format design with explicit version identification supports backward compatibility while enabling future enhancements without breaking existing parsers.

2.3 The BMDComposer: Software Overview

The development of an innovative data format necessitates corresponding software tools that can fully exploit its capabilities while providing accessible interfaces for end users. Thus, the BMD framework consists of two complementary components: the BMD format specification and BMDComposer, a comprehensive software application designed specifically for biometric multimodal data management and processing.

BMDComposer serves as the reference implementation that demonstrates the complete feature set of the BMD format while offering an intuitive user interface for researchers and practitioners working with electrophysiological signals as well as images representing biometric traits. The software manages the entire workflow from data import through final BMD file generation, encompassing visualization, annotation, compression, security, and export operations within a unified environment.

The software architecture directly supports the advanced capabilities of the BMD format through specialized modules that handle cryptographic key management, custom compression algorithm configuration, multi-level annotation creation, and real-time multi-channel signal visualization. The design philosophy prioritizes usability, enabling researchers without deep technical expertise in cryptography or signal processing to leverage sophisticated BMD features through straightforward graphical interfaces.

BMDComposer addresses the practical challenges of working with heterogeneous biometric data by providing integrated tools for common research workflows. The software handles data compression, maintains metadata consistency, validates data integrity, and ensures compliance with security requirements automatically. This integration eliminates the error-prone process of coordinating multiple tools and reduces the technical barriers that often prevent adoption of advanced data management practices.

The tight coupling between BMDComposer and the BMD format specification ensures that all innovative features remain immediately accessible to end users. Advanced capabilities such as personal data encryption, digital signature verification, and custom codec deployment operate transparently through the graphical interface, while maintaining full programmatic access for automated processing pipelines.

BMDComposer incorporates validation mechanisms that verify BMD file structure and content integrity during both creation and import operations. These checks ensure that generated files comply with format specifications and can be reliably processed by other BMD-compatible tools, supporting the long-term goal of establishing BMD as an interoperable standard for biometric data exchange.

BMDComposer implements a comprehensive graphical user interface built on the PyQt5 framework, designed to provide researchers with intuitive access to sophisticated biometric data processing capabilities. The interface architecture follows a modular tab-based design that covers all aspects of the BMD workflow while maintaining seamless data flow between functional modules.

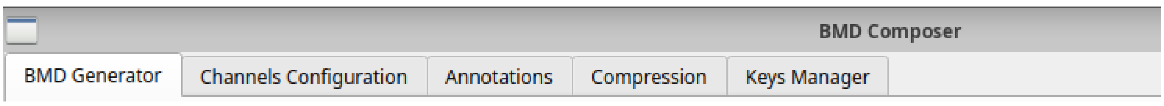

Figure 2: The tabs in the main interface of BMDComposer.

The main interface consists of five specialized tabs, shown in Fig. 2, that guide users through the complete BMD creation process: *BMD Generator* serves as the central hub for file management and export operations, *Channels Configuration* enables advanced multi-channel signal setup, *Annotations* provides comprehensive annotation tools for temporal and spatial marking, *Compression* offers customizable data compression strategies, and *Keys Manager* handles cryptographic key generation and management. This modular approach allows users to focus on specific tasks while maintaining awareness of the overall workflow progression.

The *BMD Generator* tab (see Fig. 3) implements a dual-pane layout optimized for multimodal content handling. The left pane features a file management area with dedicated import buttons for WAV and image files, accompanied by a scrollable file list that displays imported content with user-defined labels. The interface dynamically adapts to display appropriate icons and metadata for different file types, enabling rapid visual identification of dataset components. The right pane provides real-time preview capabilities that automatically switch between waveforms and images based on user selection, supporting immediate quality assessment and content verification.

The BMD Generator tab also includes dynamic form sections below the dual-pane layout for metadata management.

Dynamic form generation represents a key innovation in the interface design, particularly evident in the metadata management sections. Two dynamic forms manage fields for personal information and acquisition system parameters, respectively, allowing users to define custom metadata schemas that match their specific research requirements.

The interface provides three privacy modes for personal information - cleartext, encrypted, and anonymous - with visual indicators that clearly communicate the security status of sensitive information. This approach eliminates the rigid constraints of predefined forms while ensuring that all metadata remains properly structured within the BMD format.

Below the personal information section, the interface provides a dedicated area for acquisition system parameters where users can document technical details such as sensor configurations, acquisition systems, and device specifications. A free-form notes section complements these structured fields, enabling researchers to record contextual information, experimental observations, or methodological details that do not fit predefined metadata categories. This combination of structured and unstructured metadata capture ensures comprehensive documentation without imposing rigid constraints on research workflows.

The *Channels Configuration* tab (see Fig. 4) addresses the specialized requirements of multi-channel biometric recordings by providing comprehensive channel management capabilities. This interface enables researchers to define physical units, scale factors, and offset values for individual channels, accommodating the heterogeneous nature of multimodal recordings where different channels may represent distinct physiological measurements with varying amplitudes and baselines. The tab supports channel grouping functionality, allowing logical organization of channels based on anatomical regions, measurement types, or experimental conditions. These configurations become embedded within the BMD file metadata, ensuring that channel semantics and calibration parameters remain preserved across different analysis platforms and maintaining reproducibility of multi-channel experimental setups.

The *Annotation* tab (see Fig. 6) integrates sophisticated visualization components that support precise interaction with biometric signals. The interface supports both temporal annotations for wave segments and spatial annotations for image regions, with selection tools that provide sample-accurate positioning for time-domain signals and pixel-accurate rectangular marking for images. Multi-channel waveform widgets enable simultaneous display of multiple channels with individual scaling, units and grouping capabilities, while maintaining responsive performance for large datasets. The annotation workflow supports multi-target capabilities, allowing researchers to associate annotations with entire files, individual channels, or channel groups depending on the analytical granularity required. A dual preview system provides simultaneous visualization of the complete signal and the annotated selection, facilitating immediate comparison and validation. The interface maintains persistent annotation management with import/export capabilities for reusing annotation sets across different BMD files.

The *Compression* tab (see Fig. 8) provides comprehensive data compression capabilities through a sophisticated interface that supports multiple compression algorithms tailored for biometric signal and image data. The system accommodates standard audio codecs including FLAC for lossless compression, OGG Vorbis, MP3, Opus, and AAC for lossy compression with configurable quality parameters, alongside image compression algorithms such as PNG, JPEG, and JPEG2000. Each algorithm exposes codec-specific parameters through dedicated configuration panels, enabling fine-tuned control over compression levels, quality settings, and bitrates. The interface implements a unique preview system that performs actual compression and decompression cycles to provide real-time quality assessment, computing metrics such as Percent Root-mean-square Difference (PRD), maximum absolute error (MAE), and compression ratios (CR) before committing to final export. Users can iteratively adjust codec parameters and immediately evaluate their impact on these metrics through the preview functionality, enabling data-driven selection of compression settings that balance storage efficiency with acceptable distortion levels for specific analytical requirements.

Advanced users can leverage the Custom Encoder functionality to integrate external compression algorithms by specifying encoder and decoder executables along with their command-line interfaces, enabling seamless integration of domain-specific compression methods implemented in any programming language or execution environment. The system accommodates both script-based implementations (Python, MATLAB, R) and compiled executables, requiring only specification of input/output file options and optional parameters. Successfully configured custom encoders can be saved as named codecs within a persistent library, making specialized compression algorithms immediately available for future projects without reconfiguration.

The system automatically tracks auxiliary files generated during compression operations and maintains associations between compressed files and their related annotations, ensuring that annotation selections remain accurately synchronized with compressed signal segments. Upon completion, the tab generates detailed JSON reports documenting all compression parameters, achieved ratios, and quality metrics for reproducibility and quality assurance purposes.

The *Keys Manager* tab centralizes cryptographic key management operations required for BMD security features. The interface provides separate management sections for AES and RSA cryptographic systems, each offering both generation and loading capabilities. AES-256 encryption applies to personal data fields; users can either generate new keys from password-based key derivation (PBKDF2) or load existing 32-byte keys from file, with automatic validation ensuring key format correctness. The RSA section manages 2048-bit key pairs used for digital signatures, supporting generation of matched private-public key pairs or independent loading of existing keys with verification functionality to confirm key pair correspondence. Visual status indicators provide immediate feedback on key availability, distinguishing between loaded private keys (required for signing during export) and public keys (required for signature verification during import). The tab integrates seamlessly with other components, automatically enabling encryption and signing options in the BMD Generator when appropriate keys are loaded, and triggering automatic signature verification when public keys become available during BMD import operations. All cryptographic operations maintain keys in memory for the session duration, with an output log providing detailed feedback on all key management activities.

This cohesive design philosophy balances functional independence with operational integration, allowing users to navigate between specialized tasks without losing context or requiring manual data transfer between interface sections. The result is a comprehensive platform where sophisticated biometric data management capabilities become accessible to researchers through consistent interaction patterns and transparent automation of technical complexities.

Once all workflow steps are completed, the BMD Export button consolidates imported files, metadata, annotations, compression configurations, and security settings into a single BMD-compliant file, encapsulating the entire research dataset within the unified format.

A few screenshots of the tool are provided below. More detailed information on BMDComposer can be found in deliverable D3.2, entitled *"BMD: A New Data Exchange Format for Biometric Signals and Traits"*.

3 Acknowledgement

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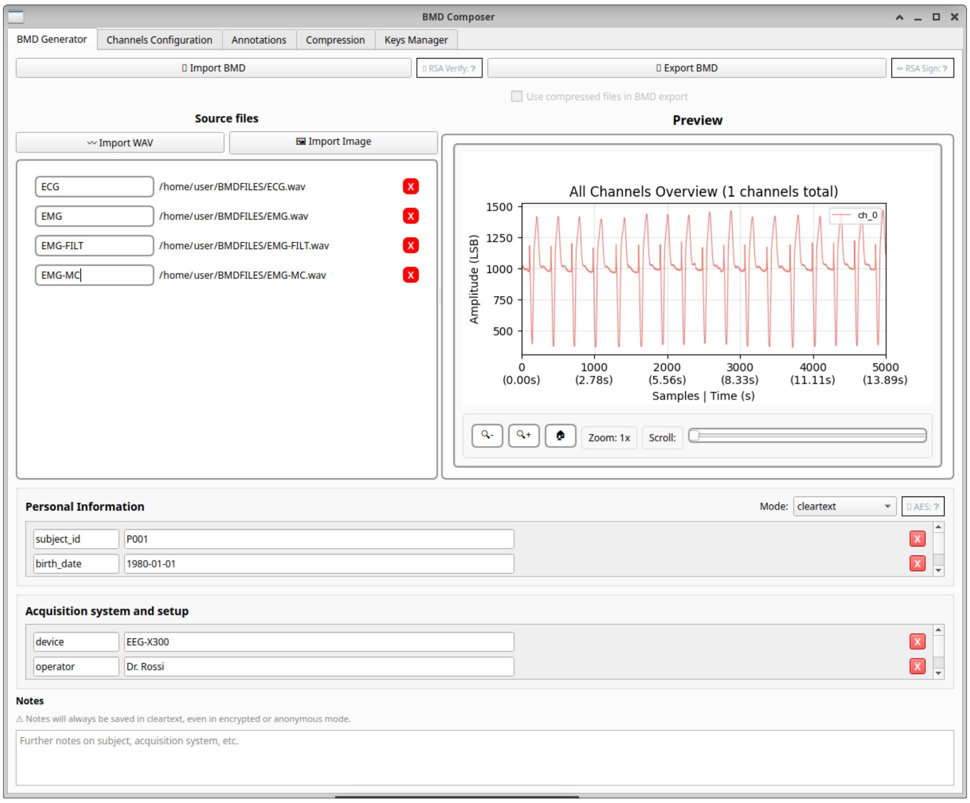

Figure 3: BMD Generator interface after importing a BMD file.

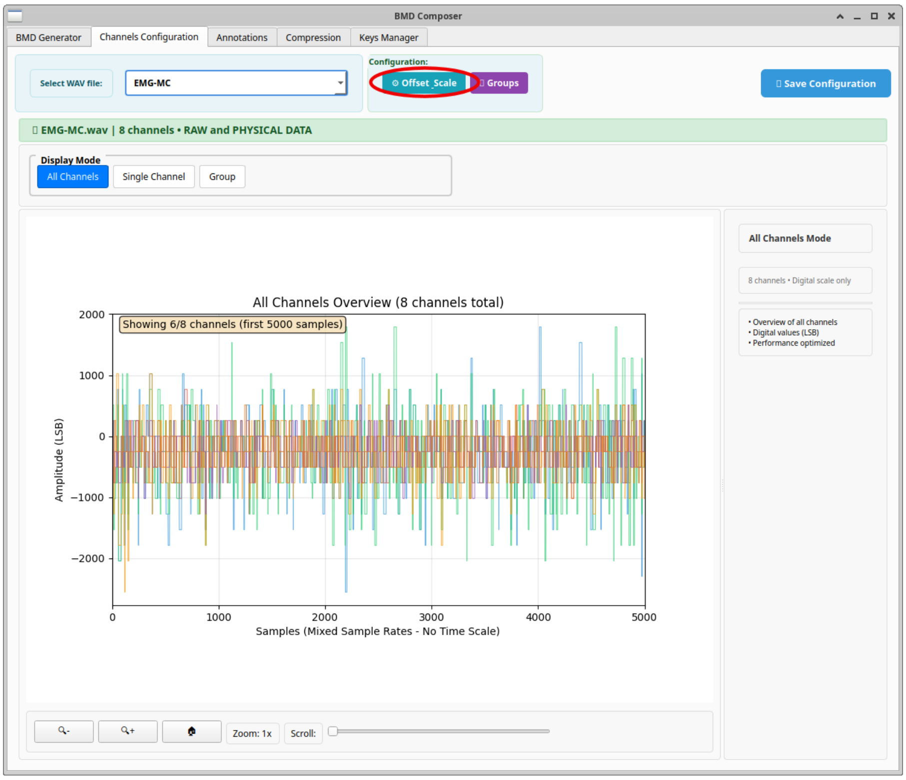

Figure 4: BMD ChannelConfiguration tab.

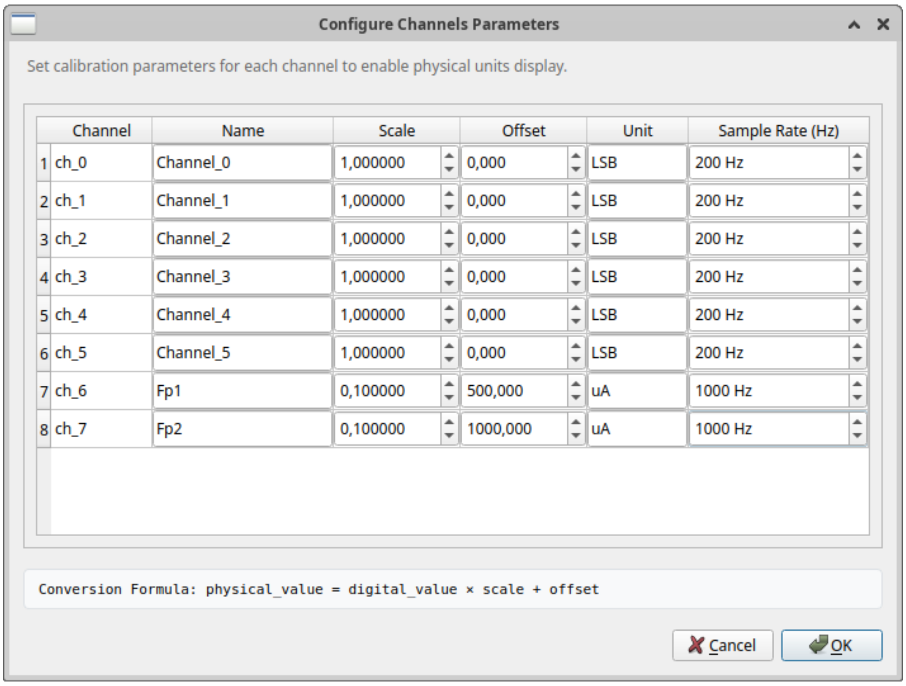

Figure 5: The physical units configuration dialog.

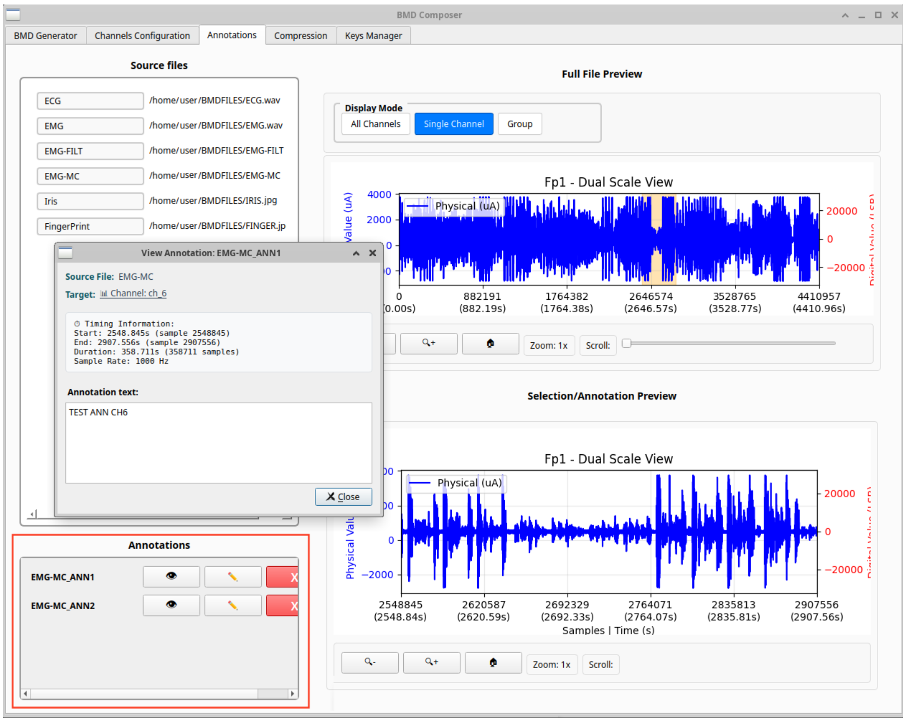

Figure 6: The annotation interface with signal annotations.

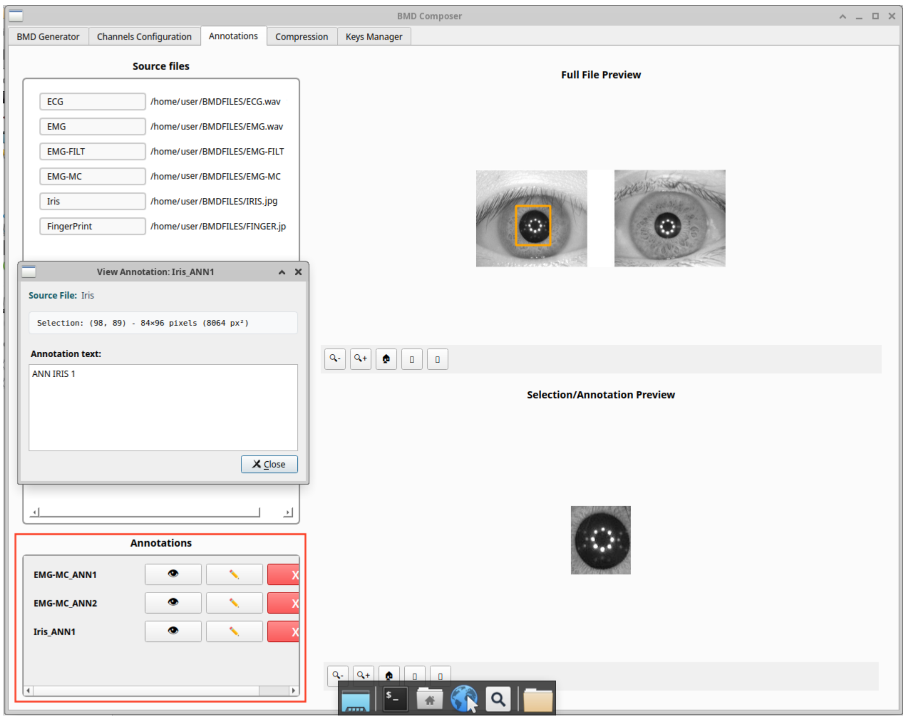

Figure 7: The annotation interface with image annotations.

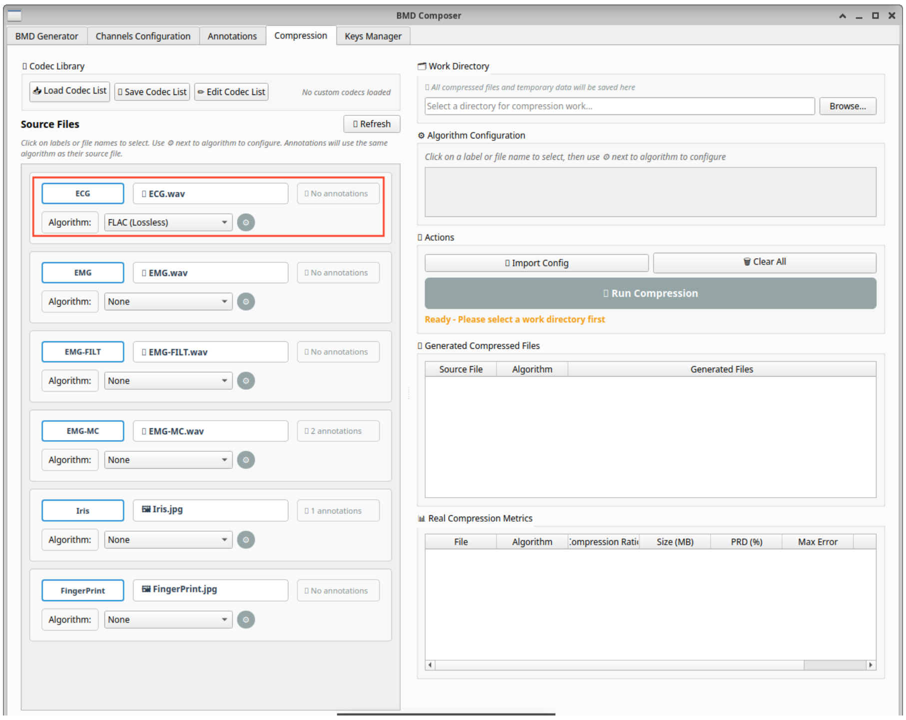

Figure 8: BMDComposer: Compression interface.

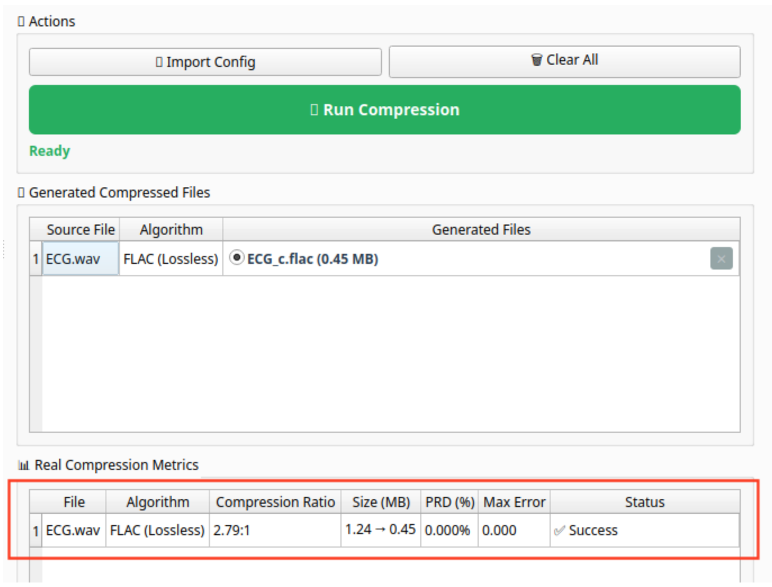

Figure 9: BMDComposer: metrics measured at the end of the compression process.