SDR-Ready Standardized Waveforms for Tactical VHF and UHF Communications for NATO

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ABSTRACT

Modern concepts of operations for multinational operations within NATO and partners require air-interface interoperability for VHF and UHF tactical communications. This contrasts with the historical approach to interoperability of using wired gateways at the higher network levels. As a result of the historical trends, national combat-net radios (CNR) have been procured from industry conforming to proprietary specifications. This has made it difficult to achieve interoperability in recent deployments, and has been a barrier to implementing modern operational concepts.

A Modern waveform providing interoperability for VHF and UHF tactical communications is under development by NATO, and this emerging standardized waveform specification is, importantly, free of intellectual property restrictions. This networking waveform is tailored for vehicle, manpack, and tank communications, for mobile ground-to-ground links, and ground-to-helicopter for rotary-air support links, providing long range secure tactical MANET supporting voice and data communications beyond 10's of kilometres distance. In the future soldiers are expected to carry small radios with soldier systems waveforms, offering broadband WiFi-like MANET services, and covering only hundreds of meters. So it should be clear that the new VHF/UHF standardization agreements (STANAGs) offer complementary capabilities to those promised in upcoming soldier radios.

1.0 INTRODUCTION

In recent military operational scenarios the need for air-interface interoperability at the tactical edge has been recognized [1] for systems commonly referred to as combat-net radios (CNRs). Unfortunately, the existing CNR communications equipment used by nations for this, usually in the 30MHz – 108MHz VHF band has not been included in any international standards, and each nation operates using different proprietary equipment. In the past, multinational interoperability has taken place at higher levels of command, and national forces operate their CNRs in national communications and cryptographic domains.

In response to this unsatisfactory situation, in 2007 NATO released a set of technical requirements for a "Narrowband Waveform (NBWF)" [2] conveying the operational military requirements in terms of engineering requirements. The NATO C3 Board's ad-hoc working group for VHF and UHF communications

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14. ABSTRACT
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has consequently produced a draft standardization agreement (STANAG) for the NBWF physical layer [3], for the APIs, and work is at an advanced stage for the access control layer and the other network elements. This NATO waveform will provide multinational interoperable communications, complementing the national tactical waveforms. The specification follows tradition within NATO in that it contains no intellectual property, which is possible because the technology has been developed primarily in government R&D laboratories. The software for implementation will be made available to nations and manufacturers via the emerging NATO Software-Defined Radio Waveform Library.

Recent improvements in modulation and coding signal processing has improved the potential throughput and range of tactical waveforms. These increased capabilities have resulted in a pull for a new generation of networked tactical radios. Traditionally, the VHF tactical band has used 25KHz channelization and 16kbps uncoded FSK modulation, with all-informed communications and no dynamic networking. The new NBWF draft STANAG provides 20kbps through 96kbps coded throughput with a fully constant envelope waveform, designed to operate at low SNR for long range networked communications at VHF and UHF. Link encryption and communications security architecture have been incorporated from the earliest stages of design, and will be briefly described in this paper.

These interoperable waveforms have been designed to conform to the footprint of legacy waveforms as much as possible, to aid the implementation in the newest generations of procured radios and in many legacy radios that have appropriate internal architectures. By using STANAG specifications, and by making available source software-defined radio (SDR) code to nations, NATO can help reduce the product development cost and development time in the deployment of this technology.

In this paper the role of tactical communications interoperability is described. The architecture of the narrowband waveform, and a summary of the main technical requirements are provided. Progress of the waveform design and prototype activities to-date is reported, including the availability of SDR software.

2.0 TACTICAL COMMUNICATIONS INTEROPERABILITY

Effectiveness of modern military operations is enhanced by the ability of terrestrial-based communications to share information in a timely manner as needed between all forces in the area of deployment. In a multinational operation, air-interface communications between forces of different nations is needed. The depiction in Figure 1 is taken from an operational and systems architecture study [1] developed to describe requirements and solutions for modern waveforms, and shows that connectivity is provided by several types of waveforms.

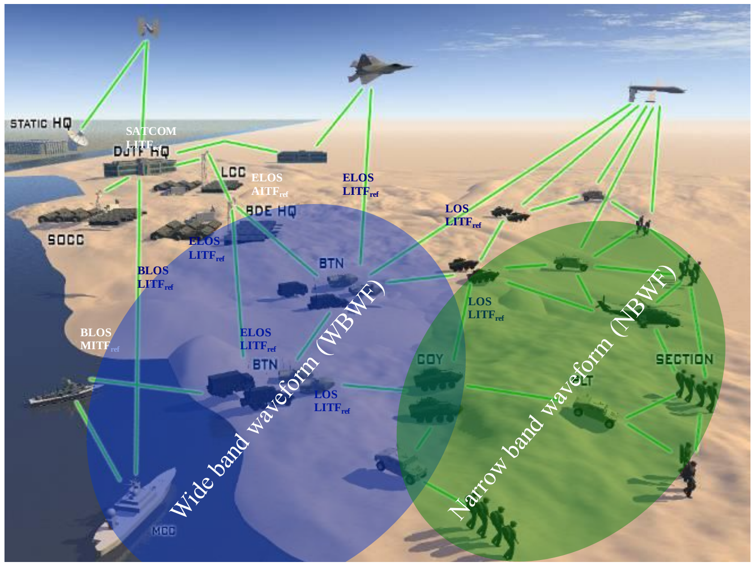

Figure 1: Operational Context of the NBWF from the Architecture Document [1].

2.1 Waveform Families

Narrowband waveform communications are traditionally secure links used by vehicle-mounted, rotor, and fixed systems that operate at VHF where each connected group of users occupies 25KHz of bandwidth. Narrowband waveform communications provides links up to 50 kilometres range due to the favourable propagation physics exhibited by the VHF band [6] and the narrow bandwidth, but with throughputs limited to about 96kbps. Many national radios use a unique proprietary waveform and do not interoperate, especially in secure modes. There is a large installed base of national radios which must be a factor in considering the overall wireless architecture

Wideband waveforms are used by vehicle mounted, fixed, and possibly air systems that operate at UHF, and occupy significantly more than the 25KHz of VHF users. Bandwidth of wideband waveforms is expected to be several MHz, following trends of commercial cellular systems. Wideband waveform links will rarely exceed approximately 5km (depending on power amplifier properties) due to the poorer propagation at the higher frequencies and the wider bandwidth, but will provide several megabits per second throughput. Wideband waveforms provide a tactical internet backbone. Some nations have already introduced high data rate or wideband systems (UK Bowman HCDR-High capacity data radio), although there is no NATO standard yet to cover this requirement.

Soldier systems communications are customized wide-bandwidth waveforms implemented on person-mounted radios that connect dismounted soldiers to each other and possibly to the wideband waveform via gateways.

Clearly the narrowband, wideband, and soldier communications systems offer complementary services. The unique features of narrowband communications are inherent long range and coverage provided by the traditional use of the 30MHZ-108MHz VHF band, and the robust communications enabled by the use of FM waveform technologies such as FSK and CPM. This standards activity described herein are specifically for modern narrowband waveforms.

2.2 Tactical Waveform Interoperability

Figure 2 depicts a multinational force, a brigade, with contributions from two nations (A and B) and the need to network with maritime and air components of nations D and C respectively. The diagram shows air interoperability points between nations where a common standardized narrowband waveform is needed. In principle, standardized waveforms can be used as the national waveform when architected to use a national cryptographic scheme. In many cases, nations have their own legacy waveforms providing national communications, and NATO standard waveforms must be able to operate with gateways into the national systems, to preserve the significant investment in legacy systems. This means that some platforms will need the NATO waveform and the national waveform, either realized on different radios or on the same radio e.g. an SDR. In this way, a nation only needs to procure or port the NATO waveform onto a small number of SDR radios, which act as gateways to national networks. Over time, new national radios may have both the national waveforms and the NATO waveforms.

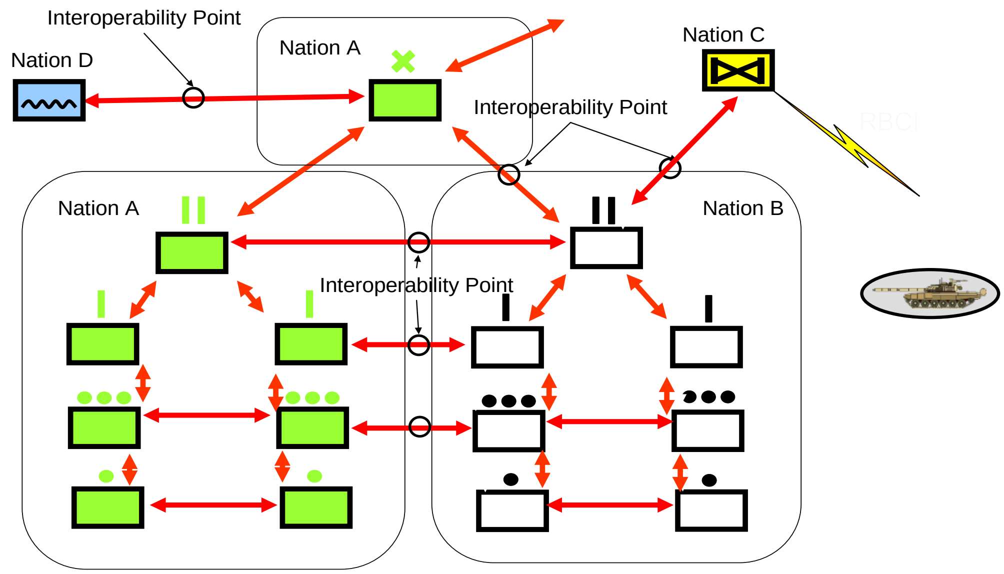

Figure 2: NBWF Pictorial Requirement, [7].

An important capability for NATO tactical waveforms is Radio Based Combat Identification (RBCI) [2]. Since the NATO NBWF will be widely deployed, it makes sense to incorporate a combat ID radio system aimed at reduce fratricide in Close Air Support (CAS) operations. This capability is intended as quick response "do not drop" to an interrogation from a friendly rotary air platform in proximity of the combat arena. Specifications for RBCI waveform are not mature, however the provisions for RBCI are being architected into the TDMA MAC for the narrowband waveform to allow hailing and response.

3.0 COOPERATIVE MULTINATIONAL APPROACH IN NATO FOR WAVEFORM DEVELOPMENT

The STANAG development effort for NBWF is described as a cooperative approach. The networked waveform is specified in a set of STANAGs. Different pieces of the radio architecture (the physical layer, MAC layer, network layer, …) are under development by different nations, and the technologies and waveform specifications are provided to NATO for standardization. The coordination of the different technologies into a cohesive networked waveform (APIs, timing relationships, etc) is done during regular meetings of the NATO Communications and Networks Subcommittee (SC/6): Ad-hoc Working Group 2, which has responsibility for VHF and UHF tactical communications. Overall architectural work, including network and security architecture is under development by the NATO C3 Agency (NC3A). The inherently costly and technically demanding waveform development is therefore shared, and the resulting set of STANAGs benefits from the combined expertise of the participating NATO and partner nations, and of NATO technical staff. The NATO SDR Users Group (SC/6 SDRUG) has initiated work to assess the impact of SDR waveforms on business models currently used by industry [7].

Figure 3 depicts the waveform sharing framework that is applicable to the definition, design and implementation of new waveforms, and is followed for the NBWF specifications. The *waveform definition* is where the contributions from each nations are consolidated together to produce the technical specifications. From the specification, the *waveform implementation* involves producing a working prototype showing the full capabilities of the waveform (including all modes of operation) and giving confidence to manufactures that the waveform specifications are complete. The initial implementation is the *Base Waveform*.

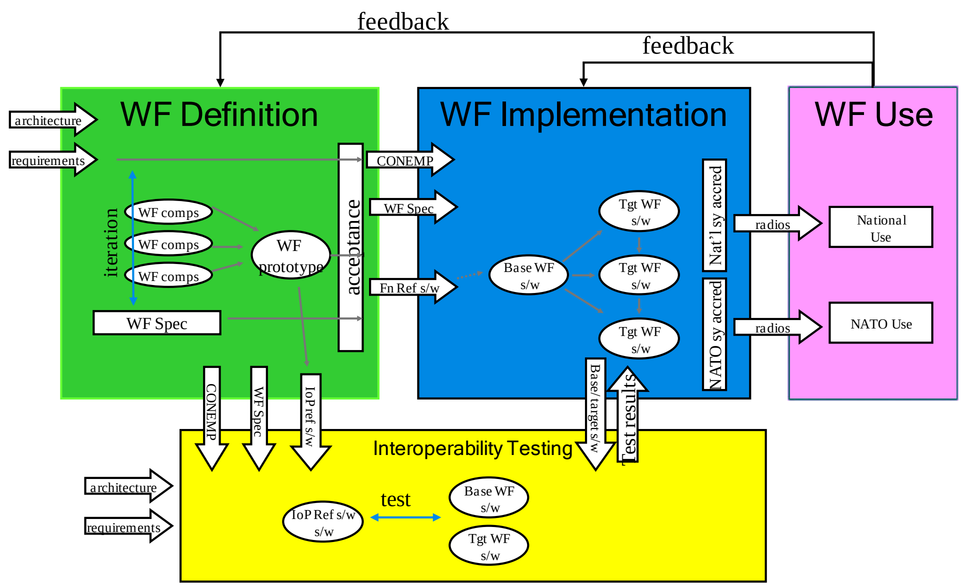

Figure 3: WF Sharing Framework.

The Base Waveform (as a specification, or as actual software implementation) is used by manufacturers to produce optimized target implementations, with architecture influenced and optimized for their radio product hardware architecture. The final product contains the target implementation of the standardized waveform, and may also contain proprietary or national waveforms. Efficiencies result from reusing the radio, acquisition, and signal processing hardware for all waveforms.

The lower box in Figure 3 shows the phase of development where interoperability is demonstrated. The base waveform is configured for full functionality testing in the interoperable test-bed, so each target implementation is tested for conformance with the NBWF STANAG. Conformance testing may be a requirement during the national procurement process to ensure interoperability.

4.0 ARCHITECTURE OF THE NARROWBAND WAVEFORM FOR MULTINATIONAL INTEROPERABILITY

Figure 4 depicts the protocol stack of the NBWF architecture for the case of a secure multicast voice call (or data), where at the top the voice application is the 2.4kbps MELPe vocoder (NATO STANAG 4591) which is encrypted by the applications COMSEC. Successively lower levels in the diagram of Figure 4 show the network layer, logical link control (LLC), the medium access control (MAC) layer, the link encryption, and the physical layer (PHY). Each layer is described by a separate STANAG, and the set of STANAGs for the different components of the waveform make up the full NBWF specification.

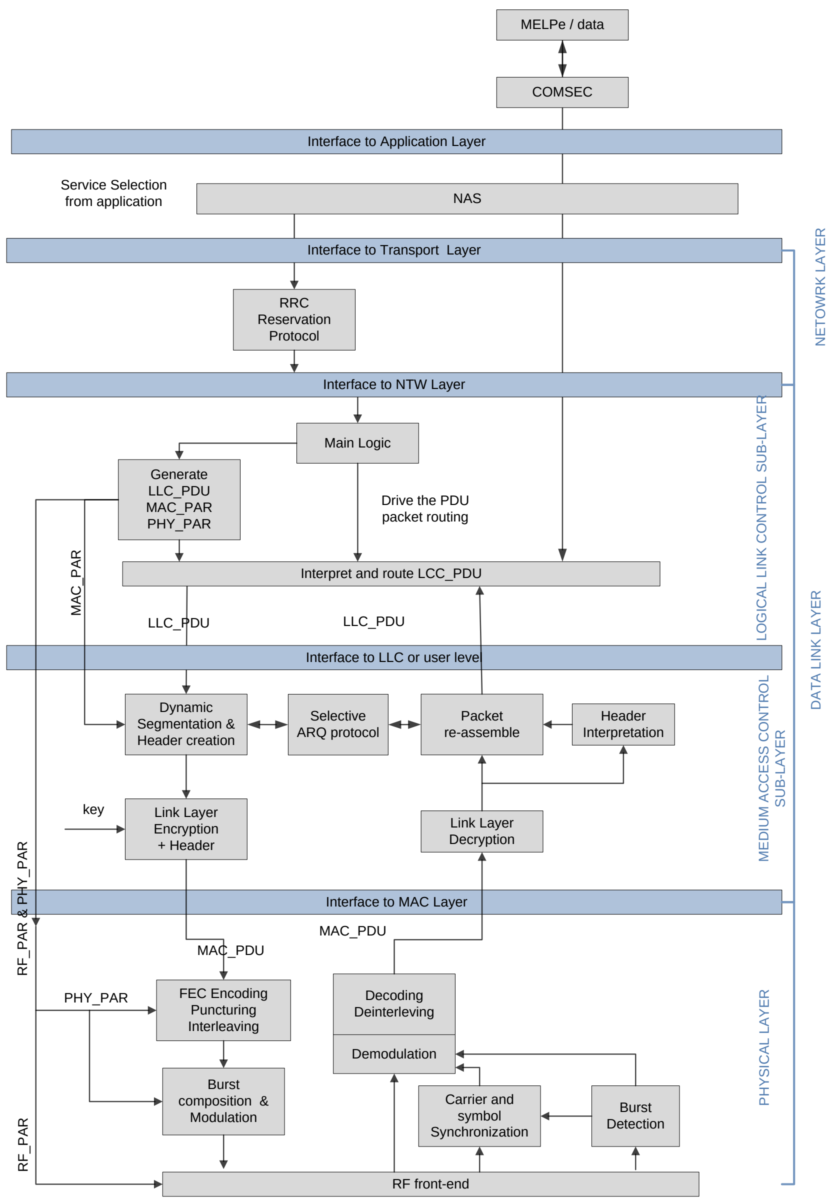

Figure 4: NBWF Notional Architecture.

The NBWF MAC layer utilizes a TDMA scheme, with no master nodes, and is specifically designed to operate within the limited on-air throughput offered by the 25KHz channels, and provide real-time voice with low latencies, including relay, taking into account latencies for radio propagation, AGC, TGC, Tx/Rx turn-around, etc. Initial prototyping will use external slot synchronization for the network, but the basic levels of ambition in the NATO requirements [2] require no single point of failure due to external synchronization.

The NBWF PHY [3] is a CPM-modulated burst waveform giving coded throughputs 20kbps, 31.5kbps, 64kbps and 96kbps in the 25KHz channels at low SNR, to maximize range. These data rates are of the payload, and do not include the impact of the acquisition preamble. In [3] there are also special short burst messages defined for network maintenance and setup. The payload modulation scheme is a serial-concatenated CPM, and the receiver has the option of using iterative demodulation and decoding for improved performance [4].

The encrypted packets directly fit the Link Control Layer (LLC) Packet Data Unit (PDU). The Reservation protocol reserves the needed resources in the appropriate time slot and the proper MAC and PHY configuration parameters are created and distributed to the respective layers. The MAC layer receives the Packet Data Unit (PDU) and segments them in order to fit the PHY layer burst. A selective ARQ protocol is used to make sure only the non received segments are retransmitted when a packet loss occurs. This process is transparent to LLC. In order to manage latency, the acknowledgement function is not enabled for voice payloads.

The Link layer encryption block protects the routing information and the radio control parameters whilst the voice payload is confidentiality protected above layer 4, where the COMSEC block is depicted. The two separate encryption functions reflect the proposed radio architecture for NATO tactical operations [1] where it is assumed that all contributing nations will be connected to a protected core network, and specific Community of Interest (CoI) with their own application confidentiality scheme are created on a needed basis. Therefore the link layer encryption keys and functionality shall be shared among all coalition partners to create the baseline network infrastructure.

5.0 PERFORMANCE OF THE PHY

The main requirement of the PHY is to support robust communications for long range communications, properly exploiting the underlying strengths of favourable VHF propagation. The secondary requirement is to maximize data rates at these long ranges. This is achieved by using constant envelope waveforms with low SNR spectrally efficient operating modes.

The PHY [3] specification describes a parameterized modem utilizing a concatenation of convolutional code, interleaver, and CPM modulation to give spectrally efficient modulation [4], as depicted in Figure 5. The properties of this arrangement allow a receiver to be constructed with a varying amount of complexity, and allows a receiver architecture with increased complexity to be rewarded with increased performance. This is desirable, since it allows manufacturers to differentiate their implementations by way of performance ie. range of operation. Figure 6 shows a block diagram of the radio receiver. The signal processing approaches conducted in the “CPM Receiver,” specifically acquisition, parameter estimation and tracking, and demodulation and decoding, will determine the performance of the receiver.

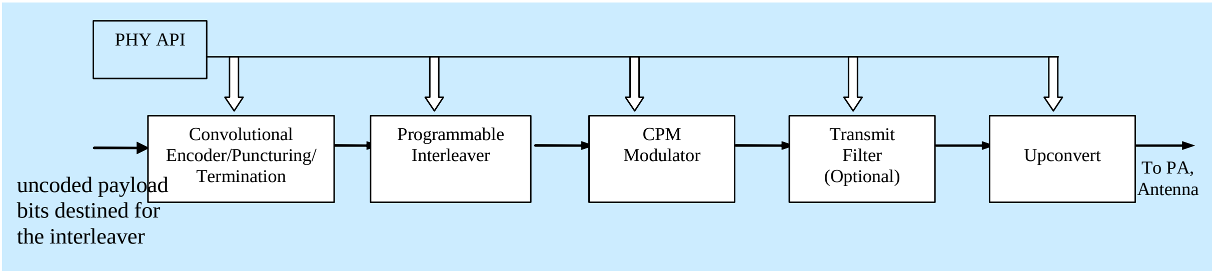

Figure 5: Block Diagram of PHY Transmit Section.

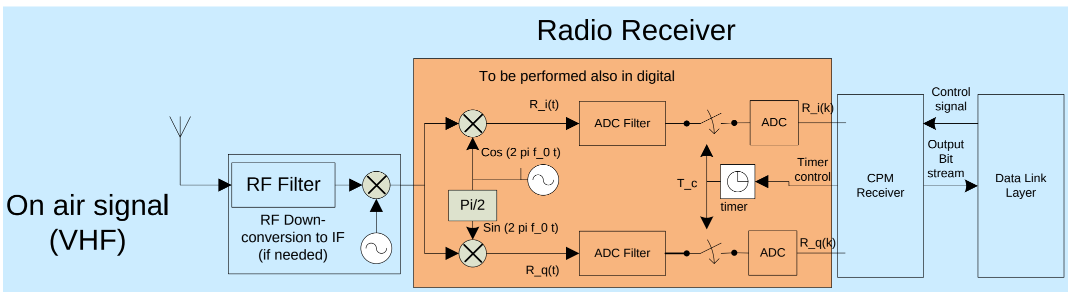

Figure 6: Block Diagram of PHY Receive Section.

In Figure 7 the Eb/No performance of the physical layer for low rate but long distance modes offering 20kbps and 31.5 kbps to the network is shown, and for high spectral efficiency modes offering 64kbps and 96kbps. Results in Figure 7 show performance with non-coherent reception with perfect frequency and timing acquisition (solid lines), and with frequency and timing acquisition included in the results (diamond lines), for a preamble duration of 45 CW symbols followed by 64 random symbols [3]. The impact of acquisition causes a minimal degradation in performance, and the trend is towards more reliability for the higher data rate modes due to the increased Eb/No for those modes. All waveform modes have constant envelope to maximize the operating range, to reduce heat generation by minimizing amplifier backoff, and to maximize the efficient use of power amplifiers.

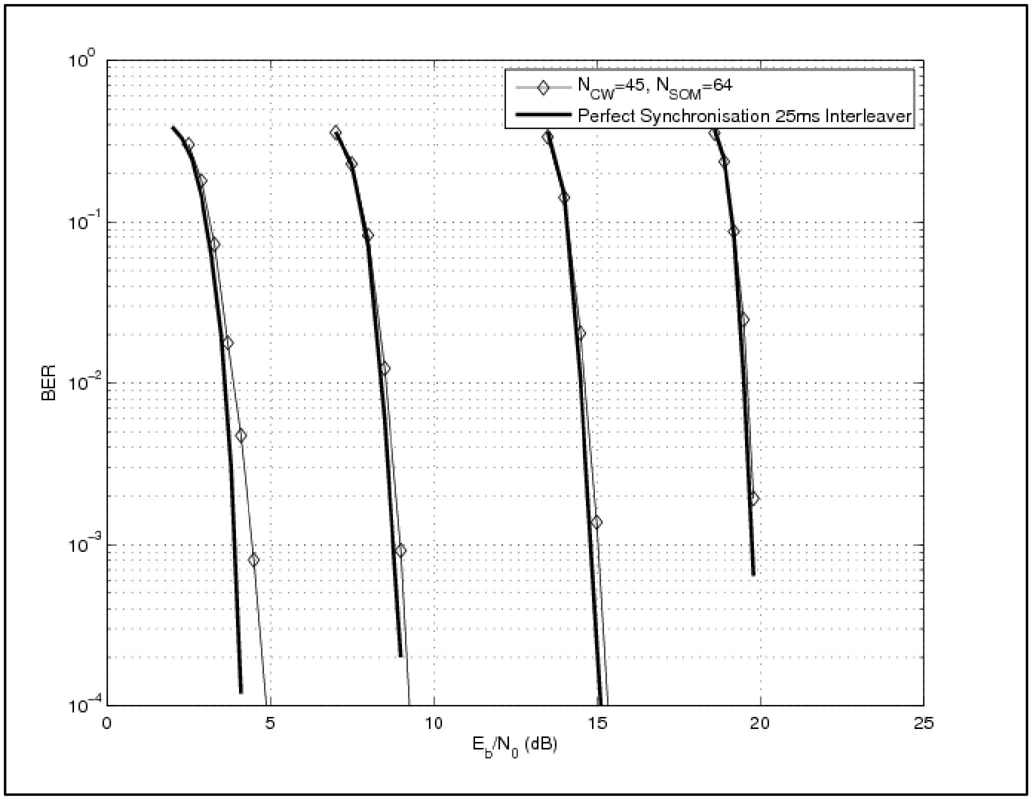

Figure 7: Simulated Performance of Four Primary PHY Modes (left-to-right 20kbps, 31.5kbps, 64kbps and 96kbps) all having 99% power in 25KHz bandwidth, and noncoherent receiver.

Both simulator and modem implementation of the NBWF have been undertaken at CRC Canada. Testing using RF channel simulator, noise source, for resilience to Doppler, channel propagation fading and multipath, noise, and Tx/Rx LO offset have been performed.

The CPM approach used in NBWF has the same envelope properties of the legacy VHF waveform, a 16kbps uncoded FSK with fully constant envelope defined in STANAG4204 [5], and improved throughput and performance. One question arises is the relative performance of the new waveform with the legacy approach. For comparison, it is important to understand the target application of the waveform. The legacy FSK in STANAG4204 is targeted to carry CVSD voice only, which operates satisfactorally at a fairly high bit error rate (BER). New networking waveforms such as NBWF are designed to carry data at low bit error rates, and utilize error correction codes as a result of this requirement. With this in mind, Figure 8 shows the performance of the 20kbps mode of the NBWF (performance designated with square icons) against the 16kbps uncoded FSK (performance indicate by diamonds.) at 8.5dB lower SNR in favour of NBWF for 10^{-4} BER. Keeping in mind that the legacy waveform is designed for an operating points at higher BERs, the SNR differential at 10^-2 BER is over 5dB in favour of the NBWF.

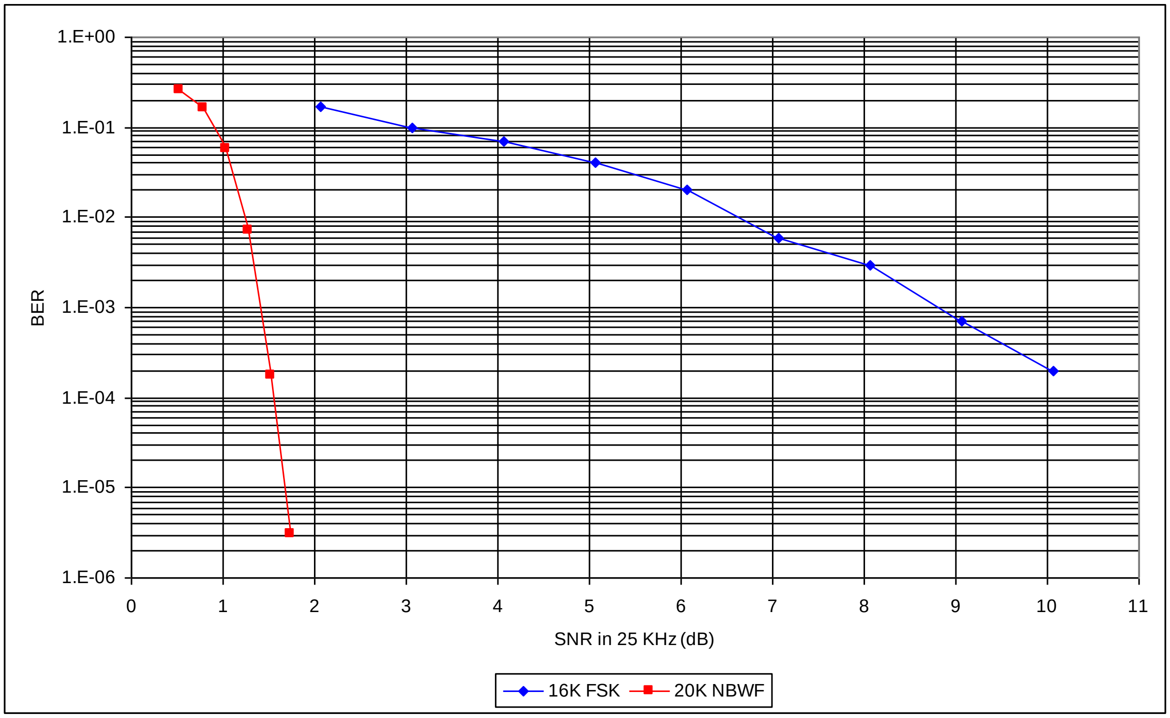

Figure 8: Compare NBWF 20kbps (100ms interleaver, coherent receiver) User to Legacy 16kbps FSK with Noncoherent Receiver (courtesy J. Nieto, Harris Corp., Rochester NY).

5.1 Prototype at NC3A in The Hague

The NATO C3 Agency has developed a MATLAB simulator environment to implement and independently assess some of the PHY STANAG functionalities in order to demonstrate its operations, as described in [8] where work has proceeded independently from the prototype work at CRC Canada [4]. The PHY layer is complemented with AES encryption algorithm and voice coding following MELPe STANAG 4591. The simulator architecture is sketched in Figure 9. It receives a voice stream coming from a microphone and samples it at 8 KHz with a resolution of 16 bits per sample. The stream is then analyzed by the MELPe encoder and passed to the AES encryption engine. From here the NBWF transmitter modulates the ciphered signal and transmits it on a VHF channel model. The NBWF receiver decodes the incoming signal and sends the estimated bit to the crypto engine which transforms it in plain text. The MELP synthesizer process the bit to eventually produce a good audible signal. The whole process is run in non real-time and uses vectors for sample transportation. Such software is available to nations contributing to the NBWF development process as means to see the capability of such radio and possibly integrate their own contribution. This development has enabled the NC3A to proactively feedback comments to the standardization group and to suggest improvements to the standard.

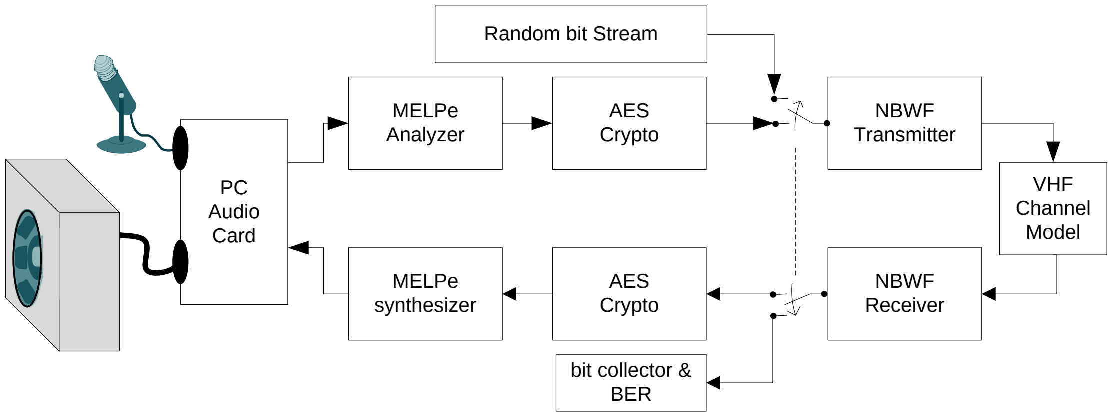

Figure 9: NC3A Functional Reference SW.

The NBWF receiver implementation at NC3A is independent from all other implementations of the NBWF and offers comparable performance to other published results (for example with Figure 7, provided by CRC Canada). The aim of assessing performance using independently conceived receivers is to show the validity and reproducibility of the performance results.

6.0 CONCLUSIONS

In this paper an overview is made of the NATO initiative to develop tactical waveform specifications for VHF and UHF communications that are free of intellectual property. Waveforms are for multinational interoperability between NATO nations and coalition users, and can be implemented on SDR platforms in tactical radios. The security architecture has been included in the design from the beginning, and performance of the waveform is targeted to be vastly improved over legacy waveforms. Capabilities of the narrowband waveform, and simulation and prototype results have been described. DRAFT STANAGS are available, and prototype software is available to NATO nations from the NATO C3 Agency (NC3A).

7.0 REFERENCES

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CRC

Defence R&D Canada

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Sept. 28, 2010 Wroclaw, Poland

Overview

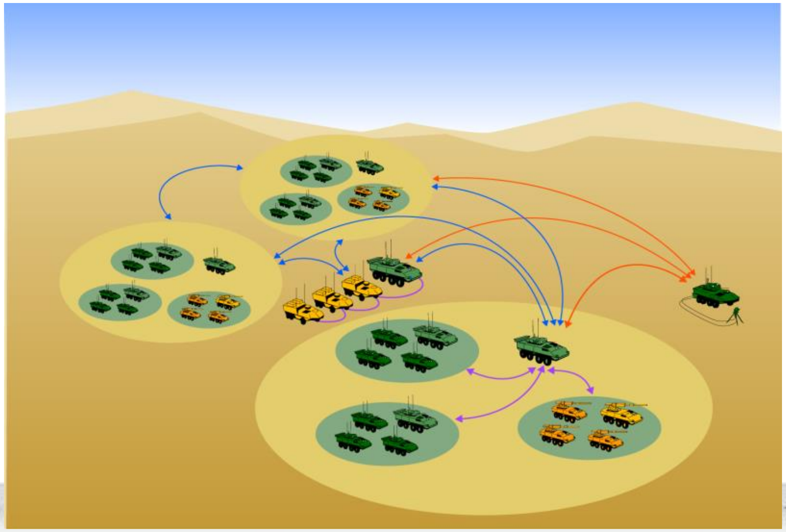
Defence R&D Canada

- Tactical communications interoperability and requirements
- Cooperative approach for waveform definition
- Architecture for Narrowband Waveform (NBWF)
- Performance of the physical layer
- Prototype

Introduction

Defence R&D Canada

- The legacy VHF tactical waveform is the basic STANAG 4204 16kbps FSK/Voice.
- Modern waveforms used by nations are generally proprietary, often without networking capabilities.
- This is different from air operations, where NATO has a rich history of coalition waveforms yielding HAVEQUICK, HAVEQUICK II, SATURN A/G/A waveforms in 225-400MHz band.
- Modern NATO CONOPS have coalition troops operating in geographical proximity, and specifies the need for air interface VHF communications STANAG.
- Such a waveform operates alongside national waveforms on a SDR platform.



NATO CONOPS Demonstrate VHF Interoperability Requirement

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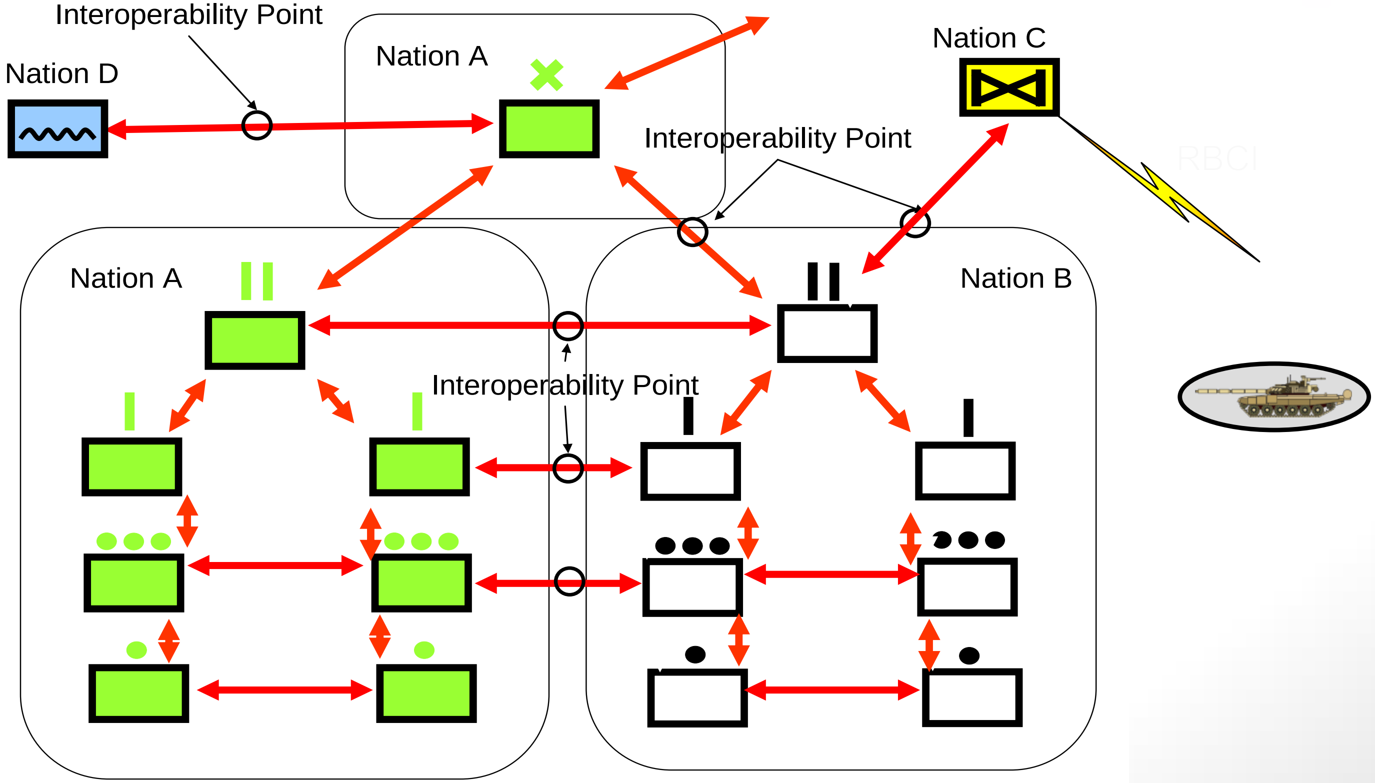
- Previously interoperability was achieved with wired gateways between nations.
- New concepts of interoperability described air-interface connectivity for land tactical radios between forces of NATO and coalition nations.



Requirements for an Interoperable Waveform

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- Requirements have been brought forward for networked communications with
  - Relay, supporting integrated voice and data,
  - Support for modern voice codecs,
  - RBCI (Radio-based combat ID),
  - Spectral efficiency,
  - EPM,
  - MANET structure with no special nodes,
  - COMSEC.
  - Others…
- Specification free of intellectual property, with a view towards SDR implementation and availability of waveforms.
- Increased data rate in the legacy 25KHz bandwidth, 30MHz-108MHz band.
- Increased robustness to interference and radio propagation impairments.

SDR Approach to Waveform Implementation and Lifecycle

Defence R&D Canada

- An incremental approach is used for new feature insertion, where extra functionality will be introduced with new versions of the interoperable equipment.
  - Allows for gradual evolution of the technology.
- SDR implementation software will be made available to nations via a NATO SDR library to facilitate “low risk” industry implementation.
  - Details of this model under development in NATO.
  - May not mean that implementation will be available at no cost.
- SDR architecture will, in principle, make it technically feasible to upgrade waveforms with low cost, since platforms are architected for regular software and firmware upgrades.
- Open architecture of platforms may mean that third parties can perform upgrades, add features.

Cooperative Multinational Development of Waveform

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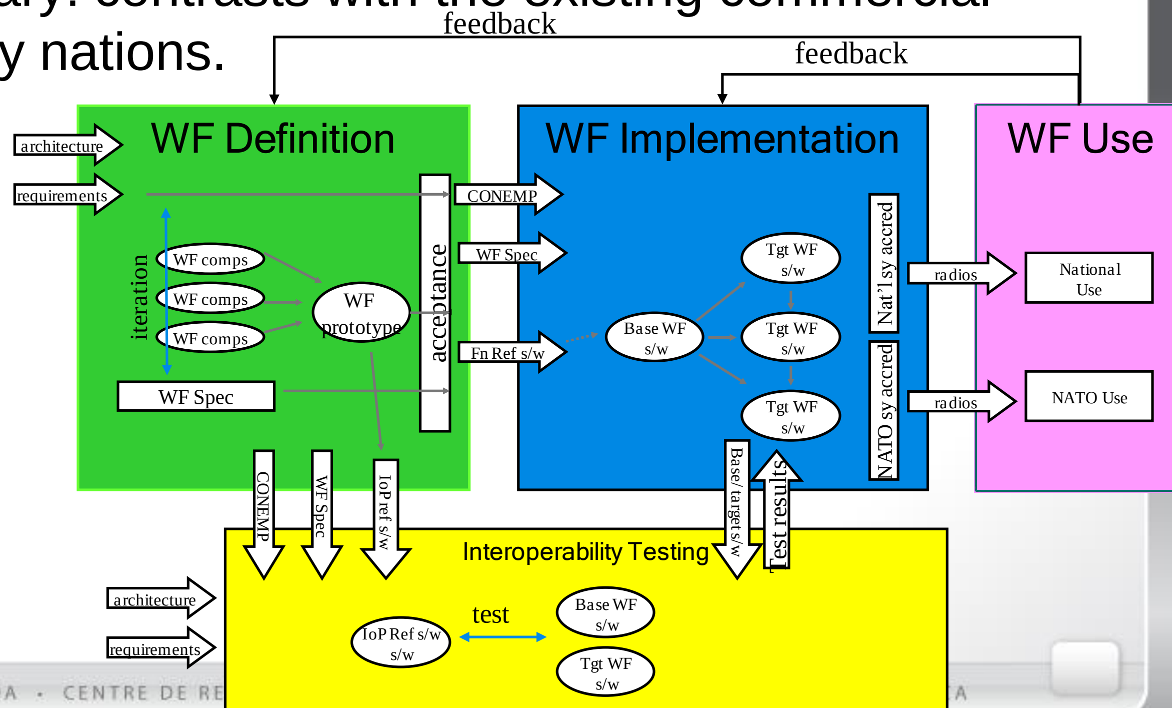
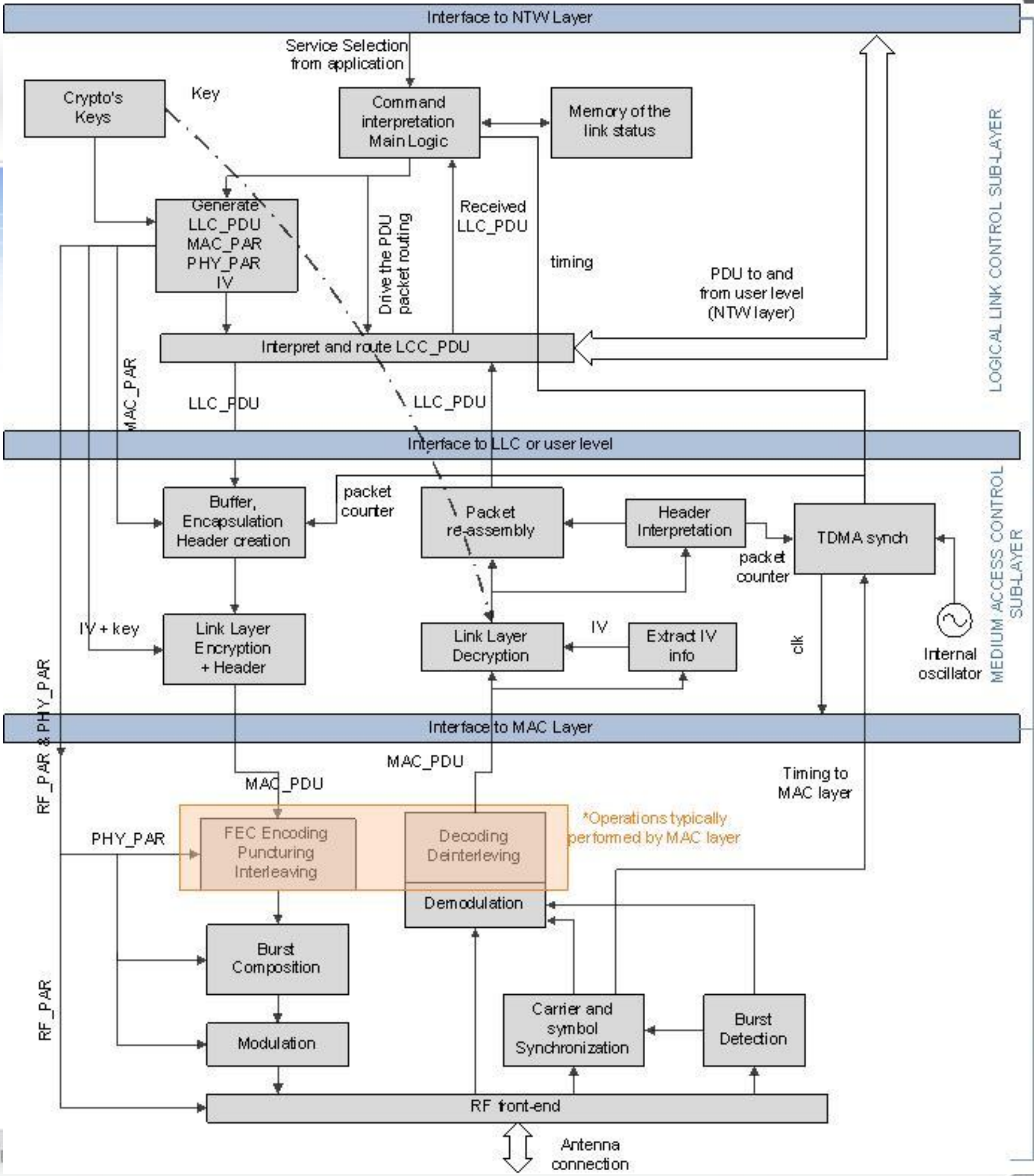
- STANAG development is the coordinated effort of several nations working within the NATO SC/6 VHF/UHF AHWG/2 standards group.
- Efforts are provided by nations.
- A valuable IP-free narrowband waveform (“NBWF”) specification is being developed.
- Waveform is non-proprietary: contrasts with the existing commercial waveforms in use today by nations.

Figure depicts work process undertaken for waveform development by partner nations. Multinational demo within a year or two…



NBWF Architecture Block Diagram

- •MAC is TDMA scheme
- •PHY is Turbo-CPM modulation
- •Voice uses 2.4kbps MELPe
- **•Security architecture not finalized**
    - •Link encryption resides above PHY
    - •Payload encryption at application layer



NBWF vs Legacy Modulation Approach

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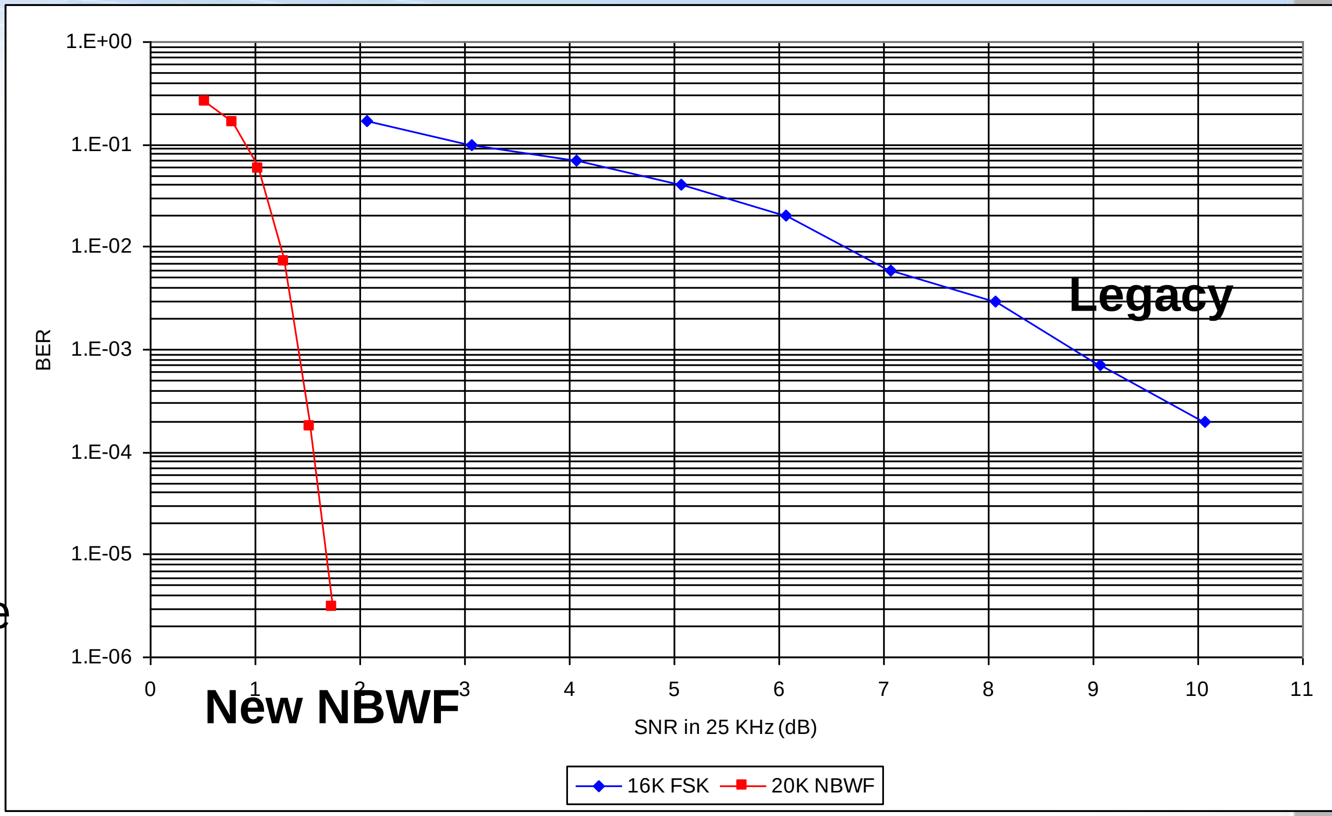
- Relative performance of legacy ST4204 FSK with new CPM approach
- Legacy: 16kbps FSK uncoded (for voice)
- NBWF: Mode 20kbps CPM coded (for voice+data)
- NBWF is ~7.5dB lower SNR than legacy at BER 10^{-3}(means greater range of communications) with more throughput



NBWF 20kbps (100ms interleaver, coherent receiver)
ST4204 16kbps FSK with noncoherent receiver
(courtesy J. Nieto, Harris Corp., Rochester NY).

NBWF Data Modes: 20kbps, 31.5kbps, 64kbps and 96kbps in 25KHz

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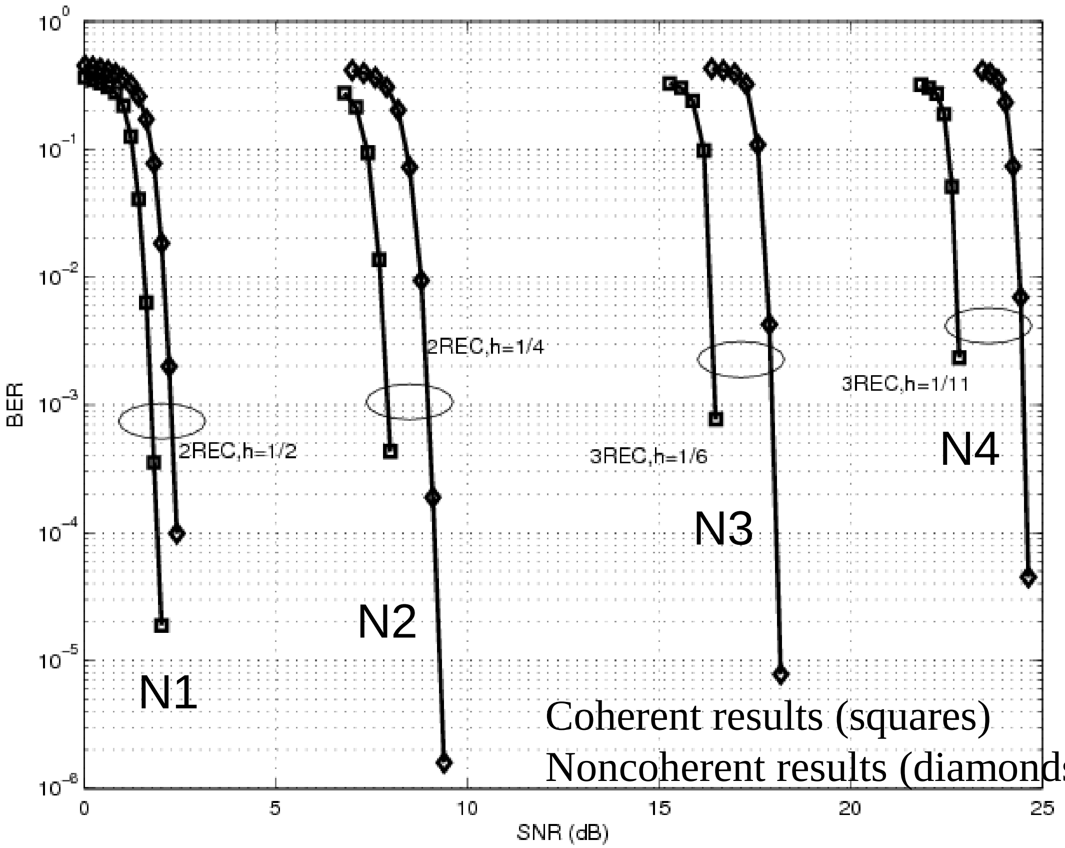

Coherent results (squares)
Noncoherent results (diamonds)

- **Spacing in SNR allows discrimination by SNR measurement.**
- **All modes 99% power within 25KHz bandwidth.**
- **Coherent and noncoherent iterative detection shown.**
- **Results shown for 25ms interleaver, 8 iterations.**
- **Reduced complexity receivers are practical.**
- **SNR calculated in relation to 99% power bandwidth.**
- **Constant Envelope.**

Prototype at NC3A

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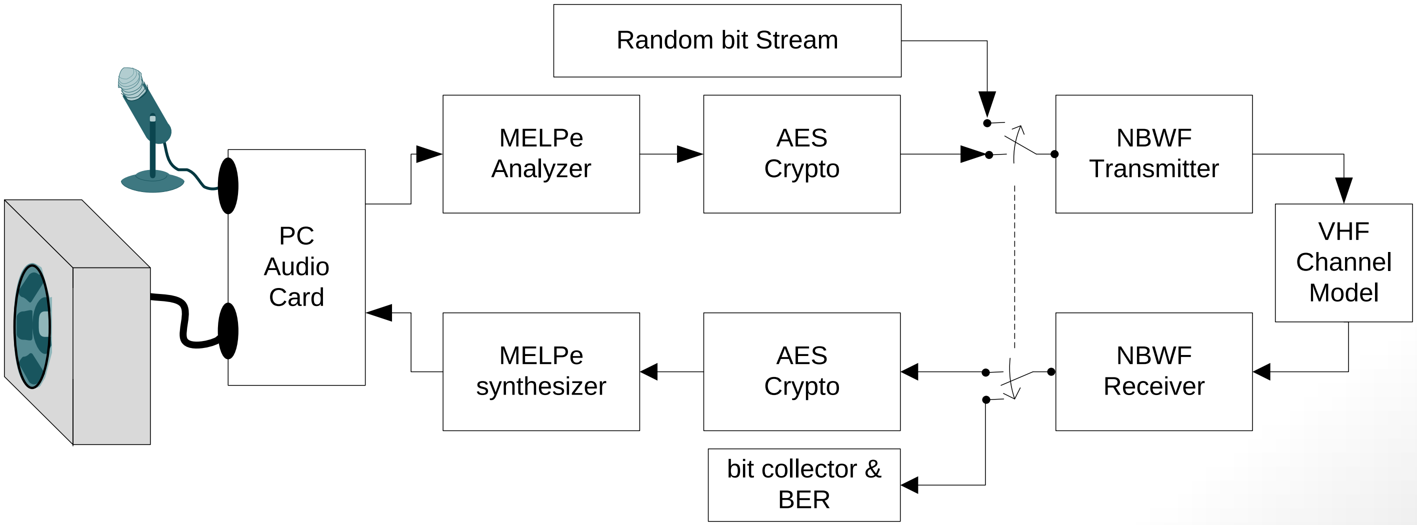
- An integrated non-realtime implementation has been developed at NC3A
- Voice remains a major requirement for VHF communications
  - MELPe codec STANAG 4591
  - Link encryption AES
  - Transmit/Receive
  - Channel
  - Platform to be integrated with MAC TDMA scheme
- Other prototypes exist in national labs.



Conclusions

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- An IP-free specification for VHF/UHF tactical communications developed in NATO.
- Provides multinational interoperability, to operate side-by-side with national waveforms in SDR platforms.
- Provides modern “turbo” waveform with networking.
- Work is progressing, contributions are from partner nations.
- Early goal is an integrated multinational demo.