First in-field Experiments with a "Bilingual" Underwater Acoustic Modem supporting the JANUS Standard

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***Abstract*—This paper presents the design, implementation, and in-field experimentation of a "bilingual" underwater acoustic modem with multi-hop networking capabilities. The designed system supports the use of the JANUS physical coding scheme and of a proprietary one. JANUS is an open, simple and robust digital coding technology currently in process to become a NATO standard. The Applicon SeaModem has been selected as the communication hardware to use and JANUS has been integrated into it. The designed system has also been interfaced with the SUNSET system which provides ad-hoc networking capabilities and the support for distributed cooperation. Additionally, SUNSET has been extended with a policy module allowing to switch between the different available communication schemes according to the network needs. In-lab experiments and in-field tests have been conducted to validate and evaluate the proposed system. A network of 4 underwater devices (three static nodes and one surface vehicle) was deployed and JANUS was used for initial contact and parameters negotiation to then switch to the proprietary communication scheme. Promising results were collected and several lessons were learnt. After the experiments a more efficient policy module has been designed and implemented and it will be tested in the next at-sea trial.**

***Index Terms*—Underwater wireless sensor networks, JANUS, SUNSET, SeaModem, Underwater digital communication standard**

I. Introduction

The interest on Underwater Wireless Networks (UWNs) has largely increased in the past decade, as demonstrated by the growing number of novel protocols and underwater communications technologies developed by Academia, Research Centers and Industry. Novel, more robust and reliable technologies have been developed to enhance the capacity and performance of communications among underwater devices and mobile assets, thus making possible to support a wide range of emerging applications: Monitoring of the environment and of critical infrastructures; prediction of underwater seismic and volcanic events; coastline protection; navigation support; etc. [1], [2].

Despite a very lively research community, and an increasing set of solutions for UWNs which have been recently designed and tested in field, development of such solutions is still not moving at the speed required by emerging applications. One of the main reasons for this reduced speed in the development and deployment of UWNs is the absence of standards for underwater digital communications. In order to cooperate, devices need to communicate and share information. Given impairments of optical and radio propagation in water, acoustic communication is often the most reliable and robust way to communicate underwater. Among the several manufacturers of underwater digital modems, none are currently able to communicate with systems produced by other manufacturers. Underwater acoustic modems currently available on the market provide quite different capabilities and performance, with a wide range of prices. It is therefore not realistic to force all possible customers to use the same acoustic modems in the different scenarios and conditions. Making the different underwater acoustic modems interoperable (supporting the use of a common "language") would result in the possibility to create underwater ad-hoc networks where heterogeneous assets can communicate, coordinate and share information.

To cope with this requirement, the NATO Centre for Maritime Research and Experimentation (CMRE) has recently promoted, in collaboration with Academia and Industry, the creation of a physical coding scheme, that allows assets to transmit information in a common format that can be decoded by compliant devices. The proposed physical coding scheme, named JANUS [3]–[6], is currently in process to become a NATO standard. JANUS provides a simple but robust digital coding technology that can be easily adopted by a wide range of existing systems.

Different acoustic modem manufactures have already expressed their intention to implement and support JANUS as a second "language" in parallel with their proprietary modulation schemes. Given the robustness achieved by JANUS and the low bit rate (80bps using the carrier frequency and bandwidth proposed in the standard), it can be easily used for two main tasks: 1) First contact mechanism to notify the presence of an asset in the area and its capabilities, similar to the Automatic Identification System (AIS) used for identifying and locating vessels; 2) Emergency channel, similar to "Channel 16 VHF" used for broadcasting distress calls such as mayday or other urgent safety messages. Once a device has announced its presence in the area and the underwater nodes have negotiated the communication parameters, they can switch to a faster and more performing modulation scheme supported by all, or a subset of, the devices in the area.

In this paper we present the implementation, use and in-field testing of a "bilingual" underwater acoustic modem supporting the JANUS standard. To the best of the authors knowledge, this is the first implementation and in-field experimentation of a complete JANUS complaint system. JANUS has been integrated in the Applicon SeaModem [7] and interfaced with the SUNSET networking system [8], [9]. SUNSET has also been extended to switch between the two communication schemes, according to the underwater asset needs. In-lab experiments and in-field tests have been conducted to validate and evaluate the first prototype of the proposed system. The in-field activities have been carried out in December 2014 at SPAWAR premises in San Diego, CA, USA, where a network of 4 nodes was deployed in the San Diego Bay. Three static nodes have been used to support the navigation and control of a surface vehicle. One static node (the control station) and the surface vehicle were able to support both JANUS and the proprietary modulation scheme, while the other two static nodes were running only the SeaModem modulation scheme.

While the surface vehicle was navigating, it used JANUS to announce its presence and capabilities (supported communication languages) to the surrounding nodes. When the control station received the vehicle message, a parameter negotiation phase started using JANUS to then switch to the modem proprietary modulation scheme in order to start exchanging data with all the nodes in the network at a higher speed. Positive results were collected during all the tests validating the considered system. More advanced "language" switching policies are currently under development and will be investigated in the next at-sea trials.

The rest of the paper is organized as follows. A detailed description of JANUS is described in Section II. In Section III we introduce the Applicon SeaModem and its integration with JANUS. SUNSET networking software and the combination with the communication and vehicle components is described in Section IV. Section V presents the experimental activities. Finally, Section VI concludes the paper.

II. JANUS

JANUS is a physical coding developed by the Centre for Maritime Research and Experimentation (CMRE), in collaboration with Academia, Industry and Government, to support the creation of an interoperable communications standard. JANUS is open-source and freely distributed under the GNU General Public License version 3. JANUS is in process to become a NATO standard (STANAG - Standardization Agreement) and it is being promoted in the maritime industry [6]. JANUS combines the public need for a standard and the NATO need for interoperability. A Frequency-Hopped Binary Frequency Shift Keying (FH-BFSK) modulation scheme has been selected for its known robustness in the harsh underwater acoustic propagation environment and for simplicity of implementation. Thirteen pairs of tones are used to encode the binary data. The pseudo-orthogonal Frequency Hopping (FH) sequence is fixed and therefore known to all potential receivers. Following the standard design, the frequency band allocation is $9440 - 13600$Hz and 11520Hz is the central frequency. The chip-rate duration is 6.25 milliseconds with a nominal bit rate of 160bps. However, JANUS has been designed in a such way that can scale to different bandwidth and carrier frequency. The bandwidth is suggested to be about one third of the selected carrier frequency Assuming a higher central frequency results in a wider frequency band usage, a shorter chip-rate duration and a higher bit rate [3] at the price of shorter communication range and lower link reliability. With a central frequency of 30 kHz and a bandwidth around 10 kHz, a bit rate of $\sim$ 190 bps is obtained. Each JANUS packet includes a header of 64 bits (of which 34 bits may be user-defined) When transmitting the JANUS header the actual bit rate is halved due to the considered error correction code. No coding is assumed for the payload that can be added to the header and the user has to protect its own data, if needed. Given the robustness of the JANUS coding scheme at the price of a low bit rate, the two primary purposes for JANUS are to announce the presence of a node and to establish the initial contact between dissimilar nodes. These purposes are similar to the "Channel 16" radio usage at sea and on land [4] to transmit short messages to the other assets of the network, e.g. distress calls such as mayday or other urgent safety messages. Additionally, JANUS can be used to implement a first contact mechanism in order to notify the presence of an asset in the area (a sort of underwater AIS) and its capabilities. In this way once a node is informed about the presence of the other nodes and the language they both can speak, the use of a faster and more performing modulation scheme can be negotiated and used to exchange data.

III. Applicon SeaModem

To the best of authors' knowledge, SeaModem is the first underwater acoustic modem entirely developed in Italy by an academic spinoff, Applicon srl, of the University of Calabria. It features a FSK modulation protocol that is well suited and robust for shallow water communications. The FSK modulation scheme is centered around 30 kHz and works in the frequency band $25 - 35$ kHz, with selectable data-rates of 750, 1500 and 2250 bps depending on the number of tones used. The modem can be controlled by any host via a standard Universal Asynchronous Receiver-Transmitter (UART) interface.

SeaModem is equipped with 16 bit CRC error detection method and with a selectable error correction scheme based on the Viterbi algorithm, whose activation halves the communication data-rate. The power transmission can be set at four different selectable steps[1] between 5W up to 40W.

SeaModem is able to calculate the distance between any two modems via both one-way and two-way protocols. The two-way protocol uses the internal Digital Signal Processing (DSP) board timer counters to measure the round-trip delay resulting in a ping test. By using the timer counters, SeaModem can measure round-trip time intervals with an accuracy of 10 microseconds resulting in a measurement accuracy around $0,015$ meters. On the contrary, the one-way protocol uses the internal Real-Time-Clock (RTC) of the DSP board that has a precision of one millisecond and a corresponding ranging accuracy of 1.5 meters (considering a sound speed of 1500 m/s). It is worth mentioning that this method works only when the clocks of the modems involved in the range measurement are synchronized and this is still a critical issue. In fact, the low-cost hardware used is not stable enough to maintain the clock synchronization for a long time and a large drift between the modems' clocks is rapidly experienced. The use of more stable RTC chips is planned in future versions of SeaModem, such as the Quantum™ miniature and chip scale atomic clock family produced by Microsemi™.

A. BeagleBone integration

SeaModem has two expansion connectors both pin-to-pin compatible with the Linux embedded platform

[1]The power transmission level can be also set remotely during the sea operations.

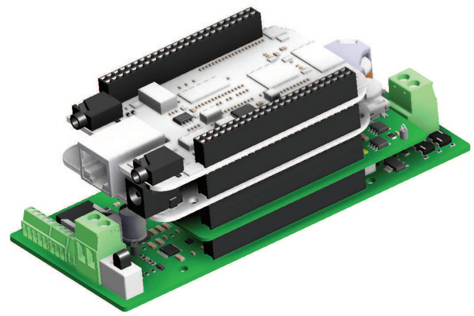

Figure 1: SeaModem stacked with BeagleBone

"BeagleBone" developed by BeagleBoard.org Foundation [10] (Figure 1). The BeagleBone board is an open-source embedded PC based on an ARM Cortex CPU running a Linux operating system. The BeagleBone acts as a host and uses the integrated UART interface to communicate with the modem. The integration with BeagleBone makes the SeaModem a stand-alone system with all the functionalities of a Linux system. Moreover, new high-level functionalities can be developed on the BeagleBone that uses the modem as a communication device.

The BeagleBone can be equipped with an additional audio codec expansion board. In this case, the codec can be used to replace the input/out functionalities of the SeaModem, for example for directly sending/receiving the acoustic signals from the piezoelectric transducer. In this configuration, the BeagleBone can be used to develop and test new modulation/demodulation algorithms or to implement new functionalities, or as a stand-alone underwater system that uses the SeaModem as a communication device.

B. JANUS implementation

Some hardware and software integration was required on SeaModem in order to integrate the JANUS software. First of all, the JANUS code was compiled for an ARM embedded platform and ported on a BeagleBone board. The BeagleBone was equipped with an external additional codec that has been used to modulate and demodulate the JANUS signals, sent out to the acoustic transducer via the modem board. In this configuration, SeaModem can use both the JANUS protocol and its proprietary protocol, switching between each other during the sea operations. The JANUS code was slightly modified to allow JANUS to control the modem board parameters via the BeagleBone GPIO. In particular, the JANUS code was enabled to activate the power amplifier in transmission mode or deactivate it during the receiving state so as to improve the Signal-to-Noise Ratio (SNR). Also, all the screen messages used in the distributed public domain version of JANUS were disabled and some code optimization for ARM platform was carried out.

It is worth pointing out that the JANUS implementation used for the in-field tests described in Section V is not fully compliant with the version currently under evaluation to become a NATO standard. The latter version of JANUS defines both a modulation scheme and a MAC implementation and assumes the frequency range of $9440 - 13600$Hz as band allocation with 11520Hz as central frequency. During the in-field experiments we only considered the modulation scheme defined in the standard and we did not make use of the JANUS MAC because as it is was not possible to complete the full implementation of JANUS before the tests. The ALOHA protocol was therefore considered as MAC. Additionally, a higher central frequency was used, around 30 kHz, in order to match the used acoustic modem transducer characteristics. A useful bandwidth of 10 kHz was selected according to the JANUS guidelines stating that a bandwidth around one third of the central frequency should be considered.

IV. SUNSET

University of Rome "La Sapienza" SENSES laboratory, has developed, in collaboration with WSENSE S.r.l., a framework to seamlessly simulate, emulate and test in field underwater communication protocols, named SUNSET for "Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing". Using SUNSET novel communications solutions can be easily implemented and tested first in a controlled simulative environment, where various scenarios and settings can be explored. These solutions can then be tested through in lab emulation and finally be used during at sea deployment (with no code rewriting) on nodes SUNSET enabled to investigate their performance in a complete underwater system. SUNSET has been ported to work on small computer-on-module hardware devices (e.g., Gumstix, IGEP and other ARM-based platforms) to be embedded inside acoustic modems or Autonomous Underwater Vehicles (AUVs) to control their functionalities. The SUNSET architecture, depicted in Figure 2, is flexible and open enough to allow the integration of any external device, once APIs are provided to control its operations. Using APIs, a driver to properly handle the device functionalities, data exchanges and interaction with the specific device can be easily implemented. Multiple software communication modules have been implemented in SUNSET to interface various hardware (e.g., sensors) and different commercial communication technologies (e.g., radio transceivers, optical modems). Additionally, the communication stack can interact in a very natural way with the navigation systems on board of unmanned surface and underwater vehicles, which is the needed feature to integrate communication and control. Using SUNSET different software and hardware components, locally present in the same network or remotely connected via Internet, can be interconnected and used to provide a more general and capable simulation and emulation framework and a distributed testing system to the end user.

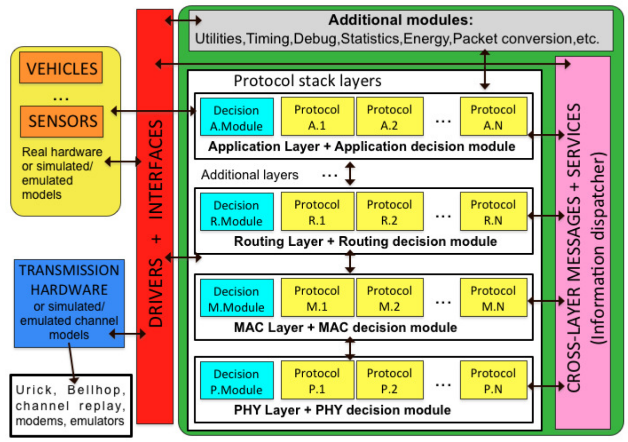

Figure 2: SUNSET architecture.

SUNSET has been extensively tested in more than fifteen in field campaigns in the past five years, considering different scenarios and conditions (sea, ocean, lake, river fjord), different network topologies (ranging from 4 to 12 nodes deployed over small and large areas), and different hardware (acoustic modems, sensors, mobile robots) and software. To fully support the Applicon SeaModem operations a new driver has been developed in SUNSET to control and reconfigure the modem, locally or via acoustic links. This driver allows to set the transmission gain, the FSK modulation, the Viterbi algorithm for forward error correction, the guard period and the chirp threshold, etc. Additionally, SUNSET has also been recently extended to fully support adaptivity (through policy or decision modules) and to support the JANUS physical coding scheme. In particular, a first implementation of a new policy module that allows to switch between different communication schemes has been developed and tested by means of in-lab experiments and in-field exercises as part of this work. Using SUNSET the underwater nodes can first use JANUS to discover each other and to collect information about the other nodes capabilities, e.g. the supported languages. Once the discovery phase has been completed, the nodes can select the most suitable language to use in order to share data.

V. Performance evaluation

A first set of in-field exercises have been carried out in the period of Nov. 26 - Dec. 3 2014 at SPAWAR Systems Center (SSC) Pacific premises in San Diego, CA, USA where four complete systems were used. Each underwater node was a stand-alone unit including SeaModem electronics, SUNSET software, SSC Pacific CPU and housing. Batteries were placed inside each unit and the modem transducer was either directly mounted to the housing (2 units out of 4) or attached using an underwater cable ($5 - -10$ m) connected to the housing (the other 2 units). Using these different configurations it was possible to place the nodes on the pier, at the bottom of the sea, at a desired depth in the water column, or on the SSC Pacific's Autonomous Surface Vehicle (ASV) that was used during the tests. In what follows we describe the underwater nodes used during the in field tests and the conducted experiments.

A. Gemellina USV

Gemellina USV (Figure 3) is a highly modified Sea Robotics USV-2600 catamaran autonomous surface vehicle equipped with above- and below-water sensors and autonomy computers. The vehicle has RTK GPS Option, Operator Interface System, and Optional RTK GPS Base Station. The system can be run in various modes of operation from manual control to fully autonomous mission execution. The design of the system is intended to maximize the use of Commercial Off The Shelf (COTS) sensing hardware and software (Embedded computer with Ubuntu 12.04LTS 32bits). The Gemellina USV system utilizes software and sensing hardware which is supplied by manufacturers and university groups other than SeaRobotics. The 4 m long, 1.9 m beam width catamaran design is an ideal solution to the requirement for shallow water (minimum draft), stable operation. The USV-2600 has a reserve payload capacity of approx. 100 kg. The architecture of the software running on payload-PC is based on MOOS-IvP [11]. MOOS-IvP is an open source C++ framework for providing autonomy to robotic platforms, in particular marine vehicles. MOOS-IvP is based on the mailbox paradigm: a community of processes subscribe to receive and publish variables from/to a database (MOOSDB). For the management and control of vehicles, the MOOS framework works according to the backseat-driver paradigm: A backseat computer executes the processes managing the mission and produces commands for a frontseat computer in charge of the vehicle low-level control. MOOS (Cross Platform Software for Robotics Research) implementation can be used for communication, networking and distributed localization and control algorithms' implementation and testing.

Figure 3: The SSC Pacific Autonomous Underwater Vehicle, named Gemellina.

B. Underwater node

Figures 4 and 5 show the underwater node and components used during the in-field tests in San Diego to provide the communication and networking functionalities. A waterproof aluminium case was used to contain the SeaModem electronic components with the BeagleBone and audio codec support. All the software to control the acoustic modem operations was running on the BeagleBone with no need of any additional board. A 16 GB SD media card was added to the BeagleBone to store the configuration files and the collected data logs. The waterproof housing was also including the battery pack and the acoustic transducer to create a stand-alone node to be easily deployed and retrieved. A $3S$ LiPo Battery with a nominal voltage of 11.1 V and 5000 mAh capacity was used. The considered battery pack was enough to last for an entire day of testing and it was recharged every night. The transducer, sealed with O-rings, was blocked on a custom case cap and connected directly to the SeaModem. The BeagleBone was configured to run at startup the JANUS and SUNSET software. Four of these nodes were used: One attached to the Gemellina ASV; one cabled to the control station and two stand-alone nodes deployed on the sea bottom with no direct access after the deployment. SUNSET remote command functionalities were used to interact with the nodes and reconfigure the SeaModem setting via acoustic messages after the node deployment.

C. In-field experiments

Figure 6 shows the network topology where the 3 static nodes and the surface vehicle were used. Node 1 was attached to a pier and it was connected to the control station. The system operator used this node to instruct the other nodes and collect the requested data. Node 2 and 4 were deployed on the sea bottom and they were used as relays to deliver the messages in the network.

Figure 4: Underwater node used during the in-field tests at SPAWAR.

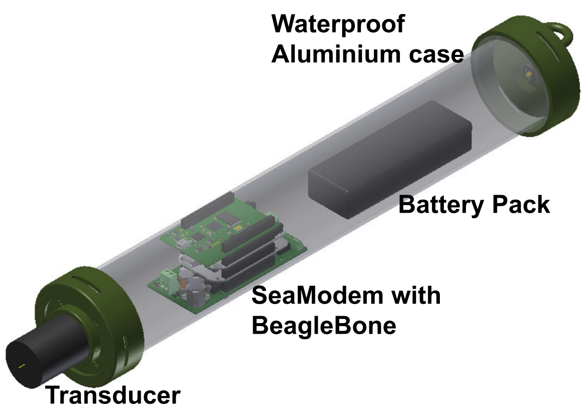

Figure 5: 3D model of the underwater node components.

The ASV, node with ID 3, was used as mobile platform navigating inside the orange area following different paths. For all the nodes the acoustic modem transducers were placed at a depth of about 1.5m. Node 1 and 3 supported JANUS and proprietary SeaModem language, while Node 2 and 4 were able to use only the proprietary language.

While the ASV was navigating in the orange area, it was using JANUS to periodically announce its presence to the control station and to then negotiate the communication parameters to use. After the negotiation phase, the ASV was switching to the agreed proprietary modulation scheme to interact with the other nodes in the network. In this case SUNSET was configured to use a carrier sensing solution (CSMA) at the MAC layer [12] and an enhanced flooding implementation [13] at the network layer. Using JANUS for first contact, discovery and negotiation is exactly the main objective behind the JANUS design.

The day when the JANUS tests were performed was the first day of testing and it was quite rainy and windy, therefore introducing some noise in the communication. Additionally, a non optimal configuration of the proprietary scheme parameters was used, resulting in a decrease in the communication performance for communication ranges longer than 150m.

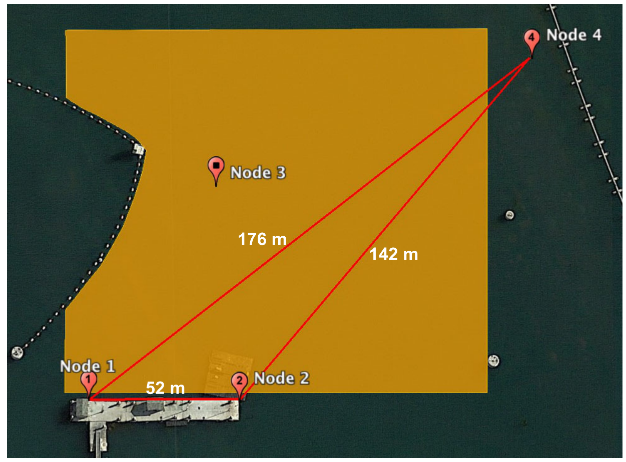

Figure 6: Nodes deployment. Node 1, 2 and 4 statically placed while the ASV (node with 3) was navigating inside the orange rectangular area.

The packet error rate, over the link connecting the surface vehicle and the control station, at different distances was near zero when using JANUS. This result is expected considering that JANUS uses a robust Frequency Hopping Binary Frequency Shift Key (FH-BFSK), a Viterbi error correction and a channel estimation algorithm. Therefore JANUS has a very low data-rate of 190 bps with central frequency of 30 kHz and a bandwidth around 10 kHz. In the same environment conditions SeaModem has a packet error rate slightly higher (lower than 0.1 in a communication range of about 400m), but it was configured with two tones Frequency Shift Key (FSK) modulation, without Viterbi error correction or channel estimation algorithm. For these reasons the data-rate of 750 bps is about four times of the one obtained using JANUS but the scheme is slightly less robust. During impairment in the communication, the system operator also used JANUS, as a robust control channel between the vehicle and the control station, to deliver messages at a lower bit rate. Overall positive results and measurements have been collected enabling to improve the designed system.

During the in-field test at SSC Pacific premises a first prototype of the policy to switch between JANUS and the property modulation scheme was implemented. It was quite simple and by default is was using JANUS as first contact and then the proprietary scheme for data exchanging. No dynamic switching among multiple schemes were assumed according to the acoustic channel condition and network geometry. Moreover, SUNSET networking feature was not fully integrated with JANUS. In the past months a complete driver for JANUS has been implemented in SUNSET and a more sophisticated policy module has been developed. This new policy considers historical information on packet delivery in the network and quality of service requirements when transmitting different messages. It selects the most suitable communication language trying to use the most performing modulation scheme in terms of transmission speed, reliability and message priority. This new policy will increase the level of flexibility and autonomy of the overall system and it will be tested in-field in the next months.

VI. Conclusions

In this paper we have presented the implementation and in-field testing of a "bilingual" underwater acoustic modem supporting the JANUS standard and the proprietary SeaModem modulation scheme. The bilingual modem has been interfaced with the SUNSET networking framework and integrated with static and mobile nodes available at the SPAWAR Systems Center Pacific. JANUS has been used to support first contact, discovery and parameters negotiation among the nodes in the network and as a reliable robust channel to exchange short control messages. After the negotiation phase, the nodes were then switching to a faster communication language to exchange larger data messages.

A network with 4 underwater nodes (three static and one mobile surface vehicle) has been deployed at SPAWAR Systems Center Pacific premises. The ASV was informing the other nodes about its presence in the area and it was then switching to the agreed proprietary modulation scheme to interact with the rest of the network. A first policy module to switch between JANUS and the proprietary modulation scheme has been implemented in SUNSET and tested in field with positive results. According to the lessons learnt in San Diego, a more advanced policy module has been implemented supporting also a full integration of JANUS with the SUNSET networking capabilities. This enhanced and more complete solution will significantly increase the level of flexibility and autonomy of the overall system and it will be tested in field in the next months.

Acknowledgment

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