Integrated PMR-Broadband-IP Network for Secure Realtime Multimedia Information Sharing

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***Abstract*—In this paper, the authors present a novel solution for the integration of TETRA-based PMR and IP based wireless broadband networks through a novel inter-system interface. This solution enables secure group communications based on PMR standards using heterogeneous devices ranging from a traditional PMR device to smart phones such as the iPhone. Thereby a Smart-phone user will be enabled to leverage on one hand the multimedia data capabilities of 3G and 4G wireless networks (UMTS, LTE) while at the same time be part of a PMR group communication. In other words, any authorized Smart-phone can become part of a PMR communication group by simply downloading the appropriate, dedicated Application. As a key benefit, homeland security personnel can be included in the disaster response actions instantaneously, without necessarily carrying around a PMR device and without the need for PMR coverage. In contrast to existing solutions, the proposed interface solution prevents the reduction of the voice quality when bridging system boundaries by tandem encoding with a TETRA-over-IP (ToIP) interconnection. The presented solutions include different interconnection setups including Trunked Mode (TMO) and Direct Mode (DMO) capabilities. To enable the group communications services as known in PMR systems, a dedicated protocol, the Push-to-X protocol developed by CNI, is leveraged. The results of performance evaluations show that the speech quality is still acceptable even under harsh conditions. The proposed system therefore paves the way towards a future, high performance PMR based on LTE, while preserving backwards compatibility with existing PMR systems.**

***Index Terms*—Public Safety Communication Network; Inter-System-Interface; TETRA; LTE**

I. Introduction

Efficient disaster preparation, recovery and response relies on secure information sharing through wireless communication systems. Standardized Digital Professional Mobile Radio systems (PMR), such as Terrestrial Trunked Radio (TETRA), have been established in recent years and provide secure voice as well as limited data services (similar to 2G commercial mobile radio systems). While commercial 3G or 4G mobile radio and WiFi-based systems provide today high performance broadband services, homeland security organizations ask for the same level of service for their purposes. While dedicated next generation professional radio systems still have a long way to go in terms of standardization as well as full deployment, there is a realistic option to enable interoperability between professional mobile radio and wireless broadband systems.

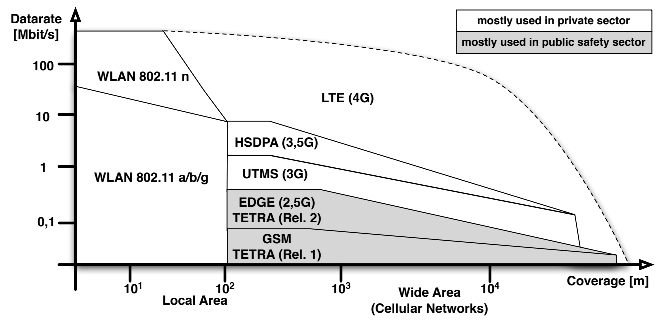


Fig. 1. Existing and Future Wireless Network Technologies

A. Evolution of Wireless Communications Systems

As depicted in Figure 1 the performance of the technologies in the private sector grows faster than in Public Safety Communication (PSC). Nowadays communication systems as 802.11 n for local networks and LTE (4G) wide area cellular networks provide data rates up to 100 MBit/s with a roadmap for the next years up to 1 GBit/s. This enables the users to rely on mobile data services and mobile Internet access in many situations, including text, voice and video communication.

The overall performance of TETRA (and similar P25 networks) is on the level as public mobile radio was 20 years ago, preventing the use of high-data rate communication such as video transmission or extensive data access. Although some enhancements are planned to the TETRA Standard (e.g. TEDS[1]), the gap between the technologies is getting greater over the time.

B. Migrations Strategies for Public Safety Communications

For the identification of suitable migration strategies for PSC systems, the needs and requirements of public safety communication are evaluated. The requirements of PSC and the fulfillment of different types of communication systems can be found in Table I. The requirements (sorted by importance) for PSC are:

- *Voice Communication:*
  Because it is the most efficient communication between

[1]Tetra Enhanced Data Service

Requirements	Professional Mobile Radio	Public Cellular Networks	Local Wireless Networks
Voice	++	++	o
Group Communication	++	-	o
Coverage	o	+(+)	-
Capacity	++	+	-
Public Safety QoS	++	-	o
Security	++	+	o
Ad-Hoc Capability / Direct Mode	+(+)	-	++
Multimedia	–	+	++

Compliment: ++ full, + partial, o rudimentary, - not complied

TABLE I
COMMUNICATIONS REQUIREMENTS OF PUBLIC SAFETY USERS

humans, most of the communication in public safety operations is based on voice.

- *Group Communication:*
  The hierarchical structure in PS-organizations lead to the need of the possibility for an efficient communication in groups. Also different features need to be covered like multi-listening groups and fast group changing.
- *Capacity optimized for high traffic load*:
  In huge scenarios the system must be able to deal at its theoretical limits to ensure stable communication links.
- *Public Safety QoS*:
  Quality of Service has a huge impact on successful communication. In dangerous scenarios, the transmission of mission critical data needs to be guaranteed.
- *Security*:
  Most of the exchanged information are either official or classified which requires a high level of security from end-to-end even over systems' boundaries.
- *Ad-Hoc Capability*:
  Incident responders require the capability of communication in every situation. Under harsh environmental conditions, the infrastructure based network could be out of order or could not provide a sufficient coverage at the incident scene. In such a case, the ability of direct communication between the responders needs to be ensured.
- *High data rates for Multimedia Communication:*
  With the increasing capabilities of public radio networks, the need for high data-rates are also growing in the public safety organizations. Online access to various information systems like [1] increase the effectiveness of rescue operations.

None of the currently available systems fulfills all requirements. The PMR systems match most of the requirements, but because of the long deployment cycles in this market, the coverage and available data rates are insufficient. Public Cellular Networks (esp. latest LTE Advanced) are not developed to match the public safety requirements, thus the specific features as group communication and direct mode is not supported. Local wireless networks provide a sufficient data rate for multimedia communication, but network management features and QoS requirements are missing.

For the Next Generation Public Safety Communication System (NG-PSCS) the authors propose the following strategy: Seamless enhancement of existing PMR systems with heterogeneous state-of-the-art technologies while the next generation system is under development. The remainder of the paper is structured as follows:

In Section II the authors outline the architecture of a Next Generation Public Safety Communication System (NG-PCS). The focus lies not on a complete specification but more on a identification of core elements and technologies for the foundation of the system. In Section III, an overview over actual research work on the interoperability of different TETRA networks is presented. In Section IV and IV-A the authors propose a gateway for the enhancement and seamless coupling of TETRA and IP-based networks, which fulfills the requirements of public safety organizations. A validation and performance evaluation of the proposed gateway is given in Section V.

II. NEXT GENERATION PUBLIC SAFETY COMMUNICATIONS

As the result of the current situation, the Next Generation Public Safety Communication System (NG-PSC) needs to perform a huge leap to the latest technologies for mobile radio communication. Compared to Table I, public cellular technologies like LTE Advanced offer sufficient performance for all kind of communication, but important features are missing. Local wireless networks provide superior data rates for short distances and are able to be connected in an ad-hoc network.

A suitable solution for the next generation communication system for public safety is a soft migration to an all IP based network which provide all necessary features as services but is independent from the underlying radio technology. The will enable the public safety organizations to benefit from the latest developments without losing the backwards compatibility to existing well established communication systems.

A first concept and evaluation of IP networks for emergency communication is presented in [2]. The results show that the use of a light-weight all IP-based peer-to-peer structure can fulfill the requirements of effective emergency communication. The lean Push-to-X protocol developed by the authors is also leveraged in the proposed new architecture and further developed.

The architecture of the proposed system is depicted in Figure 2. The fundamental features are implemented as a set of dedicated services inside the all-IP based network (e.g. *Security*, *Group Communication*, *Gateway to extended Networks*). The modular approach is elementary for the migration approach. While the NG-network is not installed in the field, other networks are coupled to the core network as *extended networks*. This intermediate solution can start with actual TETRA networks today to close the technology gap to existing systems and can seamlessly be operated until the next generation is ready.

The extended networks include public mobile networks with a good coverage and high data rates (e.g. LTE Advanced, WiMAX) as well as dedicated ad-hoc incident scene networks as described in [3]. To complete the requirements of public safety organizations, the NG-PSC also needs to implement ad-hoc and direct mode functionality. The underlying IP network can be enhanced to easily facilitate such feature. e.g. by leveraging IEEE 802.11 technologies.

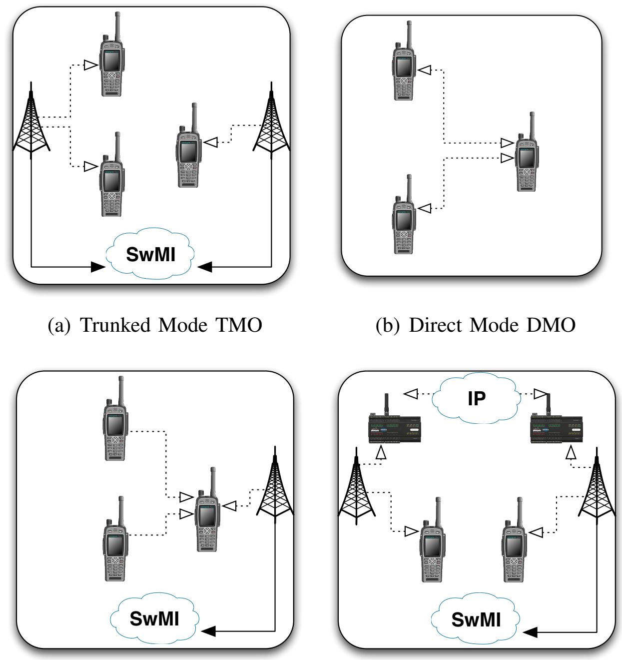
III. Solutions for an Enhancement of Existing PMR Networks

As described in Section I, incident responders need reliable and secure communication networks. Also, they should supply sufficient QoS and data rates. Worldwide TETRA networks are installed as main communication systems for public safety services. However, nowadays needs for high bandwidth data exchange is not fulfilled.

Some research has been provided for possible solutions for enhancements of existing TETRA networks. The missing implementation of real-world interconnection (except research projects like [4]) between heterogeneous systems shows that the limitations of existing and implemented inter-system interface solutions hamper seamless interconnection between trunked networks and modern communication technologies.

To understand the requirements of such solutions, the fundamental network configurations need to be analyzed. In Figure 3 the different configurations for PMR networks are shown. Figure 3(a) shows the standard trunked mode configuration (TMO). All mobile terminals are connected via a switching and management infrastructure (SwMI). In Figure 3(b) the setup for the ad-hoc or direct mode (DMO) is shown. In this mode, all terminals are connected directly (in case of out of coverage operations or infrastructure failure). The last standardized set-up is displayed in Figure 3(c). In this Gateway Mode (GMO), one terminal acts as a gateway between a DMO and a TMO configuration to enhance the networks' coverage. The idea of interconnecting PMR networks is not new. In [5], an overall description of Public Safety and Disaster Relief (PSDR) communication is presented. As an addition to a general overview, key performance indicators and parameters of such a heterogeneous communication system is given. Also [6] aims to an extension of a TETRA switching and management infrastructure (SwMI) with 802.11 access points. Therefore, an inter-working-function (IWF) is defined to include the APs to the TETRA network in the same way a base-station would be. The necessary signaling and data transmission is implemented with a full tunnel of the TETRA protocol stack with an additional adaption layer. In the same way the authors of [7] present their idea for a multi-functional TETRA gateway for industrial applications. Both solutions require to include all TETRA internal protocols (such as SNDCP[2], MM[2], CMCE[2], MLE[2], LLC[2]) in the IP tunnel, which lead to an expansion of

[2] Defined in [8]



(a) Trunked Mode TMO (b) Direct Mode DMO

(c) Gateway Mode GMO (d) Emergency Network Coupling

Fig. 3. Network Configurations for PMR Systems

the SwMI with all inherit problems, especially very restricted timing defaults. This defaults can lead to problems, if the interconnected network could not fulfill strict requirements (e.g. satellite networks [9]).

A more complex setup is the basis of [10]. The authors propose a new air interface for the interconnection of the heterogeneous systems (here: WiMAX, TETRA and TEDS[3]). Although a good solution is provided, the introduction of a new air interface (which also requires new hardware) could hamper a wide implementation.

All of the presented solutions aim at an interconnection in the IP-backbone or core network. This approach implies preceding planning and forbids flexible usage of the interface. For example, if the connection of a base station to the SwMI (core network) is broken, they operate in a fall back mode to enable local communication inside of the cell. The setup is shown in Figure 3(d). For an emergency re-establishment of the full connectivity, only a connection on the air interface can be used.

A similar set-up is basis of [11], in which the interconnection of different DMO networks over 802.11 mesh networks is outlined. Also this approach is very flexible, it is based on the standard PEI[4] interfaces of TETRA. This interface has only a PCM-audio signal defined as output for voice, what leads to a so called tandem-encoding, when the signal passes the systems' borders (TETRA to 802.11 and vice versa). The negative effect of tandem-encoding is shown in Section V.

[3] *T*etra *E*nhanced *D*ata *S*ervice
[4] *P*eripheral *E*quipment *I*nterface [12]

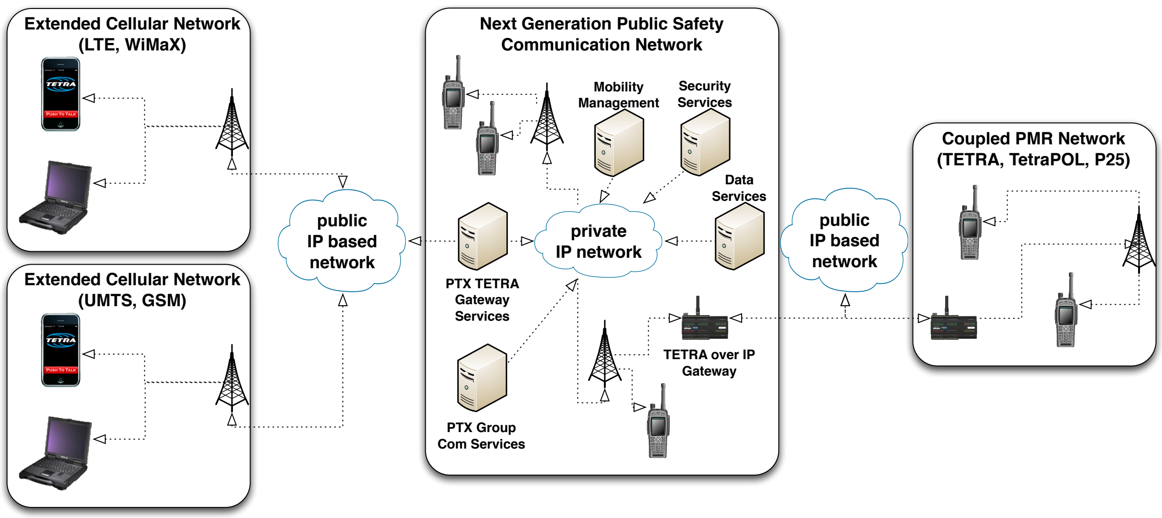


Fig. 2. Architecture of the Next Generation Public Safety Communication System

IV. TETRA over IP Gateway for extended network coupling

The aim of the proposed TETRA over IP (ToIP) Gateway is a seamless coupling of different IP-based network with existing TETRA PMR networks while avoiding the restrictions described in Section III.

As shown in Figure 2 as the *PTX TETRA Gateway*, we rely on a dedicated protocol, which combines the TETRA traffic air format with a minimal additional header for the signaling information (push-to-X: PTX). The format was developed and tested in IP-only environments under various conditions [13] and [14]. The basic frame comprises is a one Byte header extension to IP/UDP packets, in which all necessary information (as well as signaling, security and various data types) is stored. The necessary extension for the TETRA system is the use of the original TETRA air frame format [8] with ACELP [15] encoded voice including channel coding for the data transmission. This facilitates a wide range of application scenarios and services:

- TMO to TMO Link: If the connection between a subset of base stations is destroyed, the isolated network could be interconnected with the core network over any broadband IP link (e.g. WLAN, WiMAX, LTE) shown in Figure 2 on the right side.
- Multi-purpose IP interface: To enhance the usability various different technologies could be coupled to the TETRA network with a TETRA over IP Gateway (*Gateway Service*).
- DMO to TMO Link: If no infrastructure is available, terminals could also connect via the direct mode to the gateway that provides the backhaul to the core network.

A. Digital Voice Interface with Push-to-X protocol

The format of the so called Digital Voice Interface is based on the original TETRA air frame format. Because of the TDMA structure of TETRA, a frame has a size of 54 Bytes and is send out every 56,67 ms. Additional, the one Byte Push-to-X (PTX) header is added to the DVI to include the signaling information [14] as shown in II. All necessary services as *Group and User Maintenance* (including security), *Session Control*, *Codec Signaling* and *Payload Type* are included in the first three bit of the header. Followed by an bit, the last 4 bits are used for the sub-type field of the header. All types of information can be carried inside a PTX packet, therefore the 'X' represents audio, video and data transmissions.

IP (v4:20B or v6: 40B)	UDP (8B)	PTX (1B)	DVI AirFrame (54B)

TABLE II
Structure of proposed Packet Structure (with Size in Byte)

This flexible format also enables the use of different types of IP transmission, including unicast, multicast and broadcast transmission.

B. Protocol Stack and Enhanced PEI Interface

The DVI/PTX interface outlined in the last Section is based on TETRA airframes. Unfortunately the standard PEI interface has not allow to access the airframes, as The endpoints defined in PEI are layer 3 endpoints (TE2, MT2 [5]). The audio data is only available in PCM-coded format. For the mapping of the signaling, the TE2 interface provides sufficient commands, but the audio export is still insufficient. Therefore, we propose a new interface at the (D)TP-SAP[6]. At this interface, the data has the format proposed in the last section and enables the flexible usage of the new TETRA over IP (ToIP) interface. This flexibility is given by including the signaling information as a addition to the digital voice into the IP packets.

It also includes security features of the TETRA network. For a transparent coupling of two security enabled networks

[5] [12]
[6](Direct Mode) Transport-SAP

(see Figure 3(d)), the end-to-end encrypted data does not need to be decrypted (it is not possible) but can seamlessly pass the intermediate network and can be inserted in the original TETRA network.

V. Validation of Advanced Usability and Performance by Smart Phones

For the analysis of the proposed interface as well as the validation of the usability, a prototype was developed. Two versions of the graphical user interface is shown in Figure 4. The use of the iOS platform should not intend the application of such devices for incident responders but enables homeland security personal to be included in disaster response action instantaneously. Because of the outstanding importance of

(a) Landscape GUI (b) Vertical GUI

Fig. 4. GUI of Prototype Client Application

voice communication in public safety scenarios, the authors use the quality of voice transmission as the benchmark for the proposed solution. To avoid subjective test runs, the Perceptual Evaluation of Speech Quality (PESQ) standard[7] is used. It is a family of algorithms and procedures comprising a test methodology for automated assessment of the speech quality as experienced by a user of a telephony system. PESQ is an accepted and applied ITU standard for objective voice quality testing. It is a full reference algorithm that evaluates the differences between the original sample and the transmitted. The result is a value for the mean opinion score (MOS)[8], an expression for the subjective quality between 5 (excellent) and 1 (bad).

Another advantage of the proposed system is the gain of voice quality while passing network borders. In state-of-the-art systems (see Section III), the voice data need to be multiple encoded every time it crosses a systems' border. This is caused by the available interfaces, which are based on PCM transmission or standard VoIP protocols. The negative influence is shown in Figure 5.

For this test, the authors use original voice samples taken from actual emergency operations. The setup for single encoding represents a standard PMR system, in which the PCM recorded voice is encoded with the ACELP codec for the transmission to the receiver. The results indicate the good performance of the encoder, nearly all samples could match the requirements ($PESQ - MOS \geq 3.02$). Also, the use of the

[7]ITU-T Recommendation P.862

[8]ITU-T Recommendation P.800

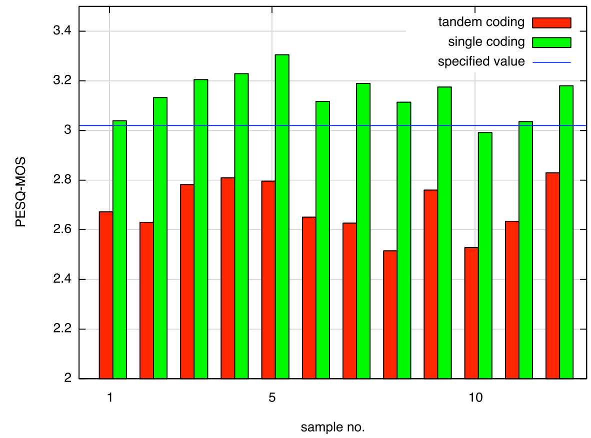


Fig. 5. Performance Evaluation of Tandem Encoding

proposed PTX-TETRA Gateway avoids the re-encoding while passings the systems' borders and has the same quality as a homogeneous system.

In contrast the tandem encoding setup indicate the performance of standard network coupling. In this setup, the voice need to be encoded at least twice. The first time to be transmitted over the TETRA air interface and the second time for the transmission in the extended network (i.e. WLAN ad-hoc or LTE public network). The lossy encoding lead to a decrease of the voice quality which can hamper an appropriate communication under contrary conditions.

Beside the superior voice quality, the use of the original air data format and speech coding including the corresponding channel coding also increases the robustness of the transmission against different types of errors in the extended network.

For this paper, we focused the stress test of the system on two different types of errors which can occur in extended networks: bit errors and packet losses. The first error type could be the result of too much interferences at the incident scene, either caused by faulty working public networks or by other incident scene networks as described in Section II. A study of typical bit error patterns of WLAN networks is given in [16]. We used a network-in-the-simulation to inject the errors in the voice transmission. To identify the limits of the system, extreme error rates as the worst case are simulated, which should not occur in real systems. The tests are run 100 times each. The results are depicted in Figure 6 and it can be seen that although the average quality is decreasing, the air encoded packets can still be used for communication up to an error-rate of 10^{-4}. The increasing and varying maximum quality of the stress-tests show the limitations of the PESQ algorithm. Because it is based on mathematical difference analysis, in some cases the result is identified as a good transmission although the voice quality is insufficient as tested by a subjective check from human users.

In the second stress test setup, the influence of packet loss is measured. The results show that the PESQ value remains acceptable up to 20% packet loss rate. The reason for this

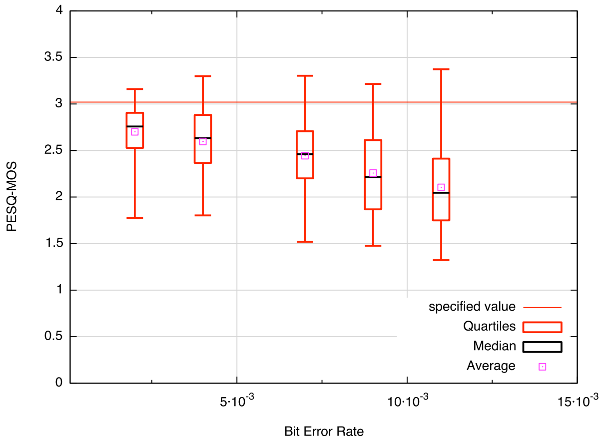


Fig. 6. Result of Stress Test: Bit Error Rates

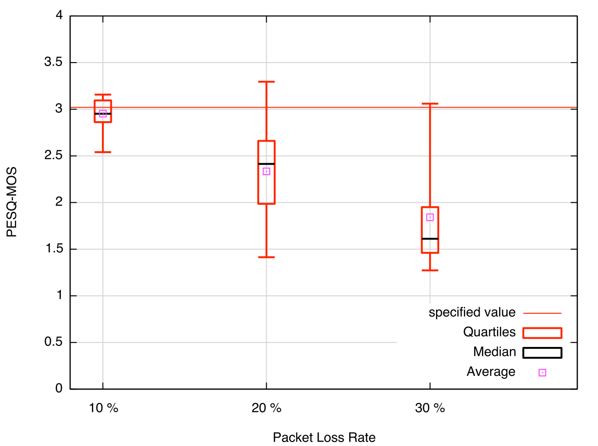


Fig. 7. Result of Stress Test: Packet Loss Rate

quite robust behavior is the small packet size of 54 Bytes. A lost packet represents a gap of 50ms in the uncompressed voice stream, which can be tolerated by the human ear within certain boundaries.

VI. Conclusion

In this paper an innovative system architecture to integrated PMR systems with IP-based wireless broadband system is proposed and validated through a prototype development. The evaluations performed with the prototype show that is feasible to operate PMR services (in this case based on the TETRA standard) with broadband cellular networks and WLAN. Thereby an important gap between limited bandwidth PMR and todays 3G and 4G broadband wireless systems can be closed. The Push-to-X protocol developed by CNI has proven to be suitable to support group communications similar to PMR services in the IP world.

The prototype realization for a SmartPhone and corresponding performance stress tests for harsh communication conditions have demonstrated that SmartPhones can be directly integrated by installing an appropriate application in PMR group communications, enabling the communication in critical situations even with homeland security personnel operating out-of-PMR-coverage. The proposed system therefore paves the way towards a future, high performance PMR/PSC based on LTE, while preserving backwards compatibility with existing PMR systems.

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