Ref. Ares(2014)2062627 - 24/06/2014

ICT- 619555 RESCUE

D1.1 Version 1.0

System scenarios and technical requirements

Contractual Date of Delivery to the CEC:	04/2014
Actual Date of Delivery to the CEC:	05/2014
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Participants:	AGH, JAIST, TCS, TUD, UBITECH, UNIS, UOULU
Work package:	WP1 - Theoretical analyses for limit and rate-distortion region
Estimated person months:	30
Security:	**PU**
Nature:	**R**
Version:	1.0
Total number of pages:	40

Abstract: The RESCUE project – "Links-on-the-fly Technology for Robust, Efficient, and Smart Communication in Unpredictable Environments" – introduces a communication concept based on distributed turbo codes, targeted for multi-hop communication in mesh networks that are subject to dynamic topology changes. This deliverable describes two potential system scenarios, i.e., network layouts with communication applications, where the RESCUE system can in practice improve reliability and spectral efficiency. The first scenario is *public safety operations* that take place in areas where the communication infrastructure is partially inoperable due to a disaster such as an earthquake. The second scenario is *vehicle-to-vehicle* (V2V) communication, where cars and other vehicles share, for example, safety-critical information about the road and traffic conditions with each other. The key functional requirements and design challenges for different protocol layers, from the physical to the network layer, are also listed. The document provides a framework for the research and validation work in the project, from analyses and simulations to field trials.

Keyword list: distributed turbo code, lossy links, multi-hop communication, public safety, vehicle-to-vehicle, wireless networks

Disclaimer:

Executive Summary

The basis of the RESCUE project is in the design and research of a novel communication concept called “links-on-the-fly”. This technology design is targeted for multi-hop communications in largely unplanned mesh networks that are further subject to dynamic topology changes. Firstly, the design takes advantage of the inherent broadcast nature of the radio channel, and the multi-route diversity of the mesh network so that the communication reliability increases, and the outage probability reduces. Secondly, the overall spectral efficiency and communication range are enhanced by the fact that even the erroneously decoded data packet transmissions are utilized, as the relay nodes may re-encode and re-transmit them towards the destination. The underlying idea is that the different transmitting nodes in the network form together a distributed turbo code that the destination can iteratively decode even if the channel (link) conditions between different nodes are mainly unknown. One of the main challenges of the RESCUE project is to discover efficient “soft” routing protocols that support distributed turbo coding under topology changes, and can facilitate a variety of unicast and multicast services.

One potential practical framework for the links-on-the-fly concept is *public safety operations* that take place in areas where the communication infrastructure is partially inoperable due to a disaster such as earthquake. In a fast emergency network roll-out the destinations may be multiple wireless hops away from the originating transmitters. Furthermore, the nodes may be moving, which results in changing channel conditions, where the changes are often unpredictable, and – in larger scale – network topology changes. The traditional public safety applications to be supported are push-to-talk (PTT) and blue force tracking (BFT), but more advanced services such as video streaming are highly valuable for public safety operations as well. Another potential framework is *vehicle-to-vehicle* communication. Here, cars and other vehicles share, for example, safety-critical information about the road and traffic conditions with each other. The vehicles form a mesh network, where the node distances and the channel conditions may vary greatly as a result of constant node movements. Thus, the network is subject to frequent topology changes, and the main challenge is in the design of a routing protocol that is always able to react rapidly enough.

The identified communication applications such as video streaming, text messaging, group communication (push-to-talk), and blue force tracking, have all somewhat different quality-of-service (QoS) requirements in terms of throughput and latency. Furthermore, the multi-hop and multi-route network structure sets a variety of functional requirements for the different protocol layers, from the physical layer to the network layer. Especially, new designs for coding and decoding, rate control, medium access control (MAC), routing, node coordination, and automatic-repeat-request (ARQ) protocols are needed. Additionally, wireless channel access and multi-antenna transmission methods matching with the RESCUE system scenarios and links-on-the-fly concept should be sought.

One important objective of this document is to lay ground for the algorithm research work in the RESCUE project by describing the main use case scenarios, applications, and conditions. Various levels of research and validation will be carried out: information theoretic analyses, model-based numerical simulations, over-the-air (OTA) testing, and – for a proof-of-concept – field trials employing programmable software-defined-radio (SDR) platform devices. Furthermore, a channel measurement campaign will be carried out in order to obtain a measurement-based vehicle-to-vehicle (V2V) channel model. The chosen scenarios and equipment for the OTA testing, field trials, and channel measurements will be described in another upcoming RESCUE deliverable [D41].

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List of Acronyms and Abbreviations

Term	Description
3GPP	3rd Generation Partnership Project
ARQ	Automatic Repeat Request
BER	Bit-Error Rate
BFT	Blue Force Tracking
CBF	Contention-Based Forwarding
CEPT	European Conference of Postal and Telecommunications Administrations
CFO	Carrier Frequency Offset
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access With Collision Avoidance
D2D	Device-to-Device
DMO	Direct Mode
DSRC	Dedicated Short-Range Communications
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FER	Frame-Error Rate
GFDM	Generalized Frequency Division Multiplexing
GPS	Global Positioning System
GSM	Global System for Mobile Communications
IDMA	Interleave Division Multiple Access
IEEE	Institute of Electrical and Electronics Engineers
ITS	Intelligent Transportation System
LLR	Logarithmic Likelihood Ratio
LOS	Line-of-Sight
LTE	Long-Term Evolution
MAC	Medium Access Control
NLOS	Non-Line of Sight
OFDM	Orthogonal Frequency-Division Multiplexing
OTA	Over-the-Air
P2P	Point-to-Point
PAPR	Peak-to-Average Power Ratio
PHY	Physical Layer
PMR	Professional Mobile Radio
PPDR	Public Protection and Disaster Relief
PTT	Push-to-Talk
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RESCUE	Links-on-the-fly Technology for Robust, Efficient, and Smart Communication in Unpredictable Environments
RSU	Radio Station Unit
SDR	Software-Defined Radio
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
TDMA	Time Division Multiple Access
TETRA	Terrestrial Trunked Radio
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad Hoc Network
WAVE	Wireless Access in Vehicular Environment
WLAN	Wireless Local Area Network

1. Introduction

The massive earthquakes including series of aftershocks hit the Tohoku and Kanto areas in Japan on March 11, 2011, followed by unprecedentedly huge tsunami waves of up to 40m height, after which numerous base stations of commercial mobile communication systems lost their proper operability. The resulting communication blackout clearly indicates that there is a need for robust technologies that can retain coverage even when the infrastructure is sparse or partially damaged. It is also highly desirable that the remaining infrastructure can be readily extended and integrated with fast ad hoc emergency wireless network roll-outs consisting of temporary or moving nodes.

One distinctive feature in a network consisting of temporary or moving nodes is that the destination may be multiple wireless hops away from the originating transmitter. Another property is that the network easily ends up having a non-hierarchical mesh structure, where the connections between nodes are unplanned and the link qualities unpredictable. Thus it is likely that there exist multiple useful multi-hop routes from the source to the destination.

The RESCUE project – "Links-on-the-fly Technology for Robust, Efficient, and Smart Communication in Unpredictable Environments" – brings forth a communication technology design targeted for multi-hop communication in largely unplanned mesh networks that are further subject to dynamic topology changes. Firstly, the design takes advantage of the inherent broadcast nature of the radio channel, and the multi-route diversity of the mesh network. Secondly, the spectral efficiency is increased by using a distributed coding method where also the erroneously decoded data packet transmissions are utilized, as the relay nodes may re-encode and re-transmit them towards the destination.

This deliverable describes two potential system scenarios, i.e., network layouts with communication applications, where the RESCUE system can in practice improve reliability and spectral efficiency. The first scenario is *public safety operations* that take place in areas where the communication infrastructure is partially inoperable due to a disaster such as an earthquake. The second scenario is *vehicle-to-vehicle* (V2V) communication, where cars and other vehicles share, for example, safety-critical information about the road and traffic conditions with each other. The key functional requirements and design challenges for different protocol layers, from the physical to the network layer, are also listed.

One important objective of this document is to lay ground for the algorithm research work in the RESCUE project by describing the main use cases, applications, and conditions. Various levels of research and validation will be carried out: information theoretic analyses, model-based numerical simulations, over-the-air (OTA) testing, and – for a proof-of-concept – field trials employing programmable software-defined-radio (SDR) platform devices. Furthermore, a channel measurement campaign will be carried out in order to obtain a measurement-based V2V channel model. The chosen scenarios and equipment for the OTA testing, field trials, and channel measurements will be described in another RESCUE deliverable [D41].

1.1 RESCUE system introduction

One of the important aspects for emergencies is the great importance of comprehensive and effective emergency management. This management is the combination of interlinked phases/responsibilities. In all these phases, communication is a major requirement for effective coordination of response operations in order to retain and maintain public safety. It also shows how much the public safety sector depends on the collection of information in such situation. It requires robustness, reliability, and high spectral efficiency, not only in terms of point-to-point communication, but also in terms of the networks. Currently, the most widely used communication systems in the case of an emergency are public protection and disaster relief networks (PPDR) such as Terrestrial Trunked Radio (TETRA) [TETRA, Gra03] and TETRAPOL. However, in the future, public safety networks and operators are expected to migrate towards broadband wireless communication systems and standards, i.e., LTE [GSB11]. One of the reasons for this migration is the larger available bandwidth of LTE enabling richer public safety services, applications and better call-quality [DDT+13]. In such critical networks, a means of communication can be provided by careful planning, deployment and efficient operation of the infrastructure.

However, one asset that might be severely destroyed in case of a catastrophe is the communication infrastructure itself. For example, in the case of the tsunami in Japan [JPN13], equipment was submerged

by the flooding, cables were cut-off or even unburied from underground, telephone poles were ripped out. Other equipment that was not broken stopped operating after battery life depleted due to long lasting commercial power outage. Even more problematically, the appropriate operation of the communication network is attacked from both sides, the limited capacity provided by the remaining infrastructure and the increasing communication demand of people who are concerned about the wellbeing of relatives, family members, and friends which causes network congestion and service saturation. Thus, means are required to distinguish different services and users in order to prioritize the exchange of data that is vital for public safety. This is increasingly difficult, because in the world of tomorrow such communication will not only relate to PPDR personnel but also all kinds of other sensors and devices, i.e., D2D and smart cities

This background motivated us to establish a theoretical, technological, and practical basis for a novel communications technology design that efficiently utilize the characteristics of future wireless networks, which are expected to be dense in terms of node and link populations, and heterogeneous in terms of their built-in capabilities. A network design based on these principles is expected to be robust and flexible towards the destruction of infrastructure but also energy and spectral-efficient.

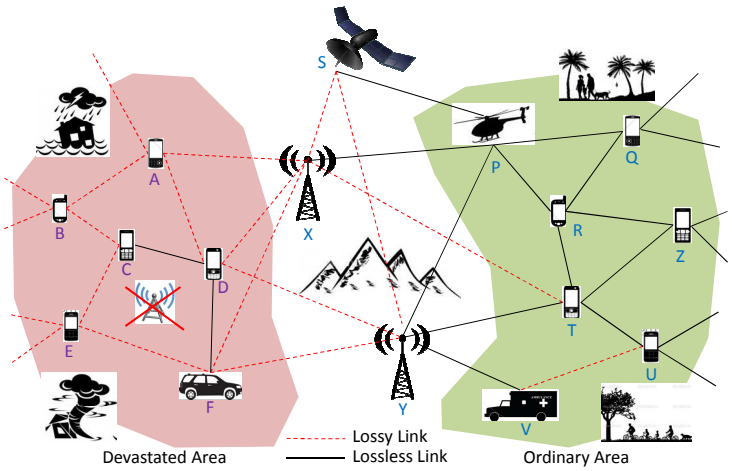


Figure 1.1: Typical public safety theater deployment.

Links-on-the-fly is a novel concept for robust, efficient, and smart information transmission in *unpredictable environments* which are characterized by substantial and sudden changes of the network's structure. The concept integrates the key technologies:

- Distributed joint source/channel coding in lossy wireless networks.
- Modern signal processing and coding/decoding algorithms (such as distributed turbo coding).
- Exploitation of multi-route information transfer in wireless multi-hop networks.
- Distributed and centralized MAC/network protocols for channel access, and routing.
- Cross layer design for interference management and error control.

Links-on-the-fly achieves:

- Successful and robust information transfer through multi-path networks that are constructed from lossy point-to-point links (*increase of coverage*).
- Adaptability of information quality to the specific quality of service (QoS) requirements of applications and devices for higher spectrum and energy efficiency.
- The integration of diverse communication infrastructure such as base stations, relays, and satellites, and terminals for network robustness and fast provision of communication services (e.g. in case of disasters).

The conventional multi-hop/mesh networks are designed on the basis of lossless links, and they are not optimal for fragile public-safety networks because:

- Functional end-to-end connections can only be achieved by accurate planning of the backhaul and the access network. Planning also includes accurate link budget allocation which, however,

does not foresee the case of huge disasters due to the potential destruction of large parts of the infrastructure.

- The required very strong coding techniques on each link causes heavy power consumption due to the decoding complexity.

As a major benefit, network design according to the links-on-the-fly concept does not have to use the accurate/strict link budget design, and it includes the whole spectrum of diverse communication infrastructure as depicted in Figure 1.1 including satellites, multi-hop communication through various terminals, which can also be carried on cars, airplanes, helicopters or even drones, etc. Furthermore, by accepting the specified level of loss/distortion, the rate/power requirements to be allocated to each link/node can be significantly reduced in the network as a whole. At the same time, robustness of the network is significantly enhanced. The expected result of this project is, hence, the key to a technological basis for the design of secure, reliable, and energy as well as spectrally efficient networks of many nodes/links that are potentially unreliable. Another important factor is that given the global requirements and recognition of the importance towards building eco-friendly society, creating new broadband wireless communication network concepts that perform close to the *network-level* limits of energy and spectrum efficiencies (as described e.g. in [EK11]), and operate beyond the traditional point-to-point (P2P) communication paradigm, is an urgent demand the achievement of which would constitute a major enhancement coming with future broadband wireless communications systems beyond LTE-Advanced.

1.2 Theoretical background

Almost 20 years have passed since the discovery of turbo coding technique by Berrou et al. that achieves near Shannon capacity on P2P links. Based on the turbo concept, as a backbone technique of commercial communication systems where the channels connecting a base station and the users are an assembly of the P2P links, many new techniques have been created. However, the cellular communications systems based on the capacity-achieving P2P link design are found to be vulnerable to network topology changes. The recognition of this vulnerability has invoked a paradigm-shift of the turbo concept from P2P optimization to network-level optimization where the network, as a whole, is regarded as a distributed turbo code.

In the distributed turbo code concept, the relay nodes – that are on parallel routes from the source to the destination – apply different interleaving patterns when re-encoding the same data packet. At the destination, the differently encoded copies are combined via iterative decoding that may correct the decoding errors that occurred at the relays. Thus, even though the quality of a link on one parallel route (intra-link quality) drops to a level that is lower than designed, the end-to-end communication may well be successful. Furthermore, by utilizing a bit-wise reliability compensation function that employs the knowledge of the intra-link error probabilities, error probability at the destination can further be reduced. This structure is found to be supported by the correlated source coding theorem, known as Slepian-Wolf theorem in Network Information Theory.

The benefits of allowing intra-link errors in cooperative wireless networks are summarized as follows:

- The information frames received at the relay node found to contain errors are not discarded but further interleaved, re-encoded, and transmitted to the next stage. By allowing the frames having intra-link errors to be forwarded, we can preserve many parallel links, some part of which may have mesh-structure, and hence we can expect significant diversity gains and reduction of the system outage.
- The reliability of the end-to-end connection is improved by link or route diversity under unpredictable link gain variations, or even topology changes. Different combinations of parallel intra-link channel gains form an *admissible rate region*, inside which any rate combination enables lossless end-to-end communication. This effect significantly reduces the outage probability of the system.
- Conversely, when the system is in a stable and predictable situation, even if the source entropy is larger than the rate supported by the channel, still source information can be recovered with the correlated source detection technique. This yields higher spectrum efficiency than the conventional techniques based on P2P optimization techniques.
- Since the achievable rate of an end-to-end connection depends on the aggregate of qualities of multiple parallel routes, the link budget can be more flexibly allocated in terms of transmit power.

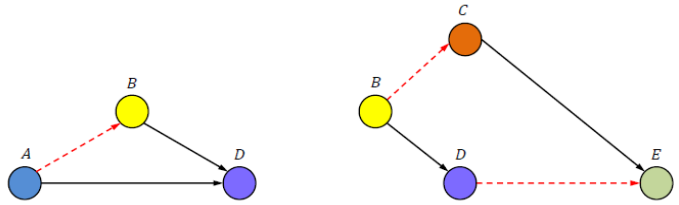
The probabilities of the intra-link errors can be estimated only at the destination (or also at the relay nodes, if the network, in part, has mesh structure), and hence no side-channel is needed. The logarithmic-likelihood-ratio (LLR) exchange is performed at the destination (or also at the relay nodes, if the network has mesh structure), where reliability compensation reflecting the intra-link qualities (or more drastically, it reflects the appearance/disappearance of the intra-links) is performed by the LLR updating function that follows the intra-link error probability estimation, yielding significant robustness against the network topology variation. This concept is referred to as "link-on-the-fly" principle.

If some level of distortion, e.g., 10^{-5} bit-error-rate (BER) or 10^{-3} frame-error-rate (FER), is accepted after the decoder at the final destination (referred to as lossy communication), we can further broaden the admissible rate region, resulting in further robustness of the network. The distortion appears in the form of error floor in BER or FER curves versus received SNR. With the system design based on this concept, we can expect significant reduction in required transmit power, while keeping the outage probability of the system as required.

1.2.1 Lossy and lossless networks

Let us define the terms lossless and lossy networks:

- Lossless network has at least one tandem connection, i.e., a set of consecutive links, where the data remains error-free before it is interleaved and re-encoded at each relay node. The problems related to this network structure can be classified into the category of lossless Slepian-Wolf correlated source coding with helpers. This system setup is exemplified as shown in Figure 1.2 (a).
- Lossy network is a network where there is no tandem connection of links where the data remains error-free before re-encoding at every relay node. The problems related to this network structure can be classified into the category of lossy correlated source coding, such as chief executive officer (CEO) problem. This system setup is exemplified as shown in Figure 1.2 (b).



(a) (b)

Figure 1.2: Examples of (a) lossless and (b) lossy networks. A dashed arrow indicates that the receiver is unable to decode the transmitted sequence error-free.

A complex network can be decomposed into some component networks, where the transmission chain structure and its related parameters can be optimized separately, but not network as a whole, since the theoretical limits are known only for specific network structures. In the networks, where the network nodes are densely populated, it is likely that there exist several routes, even though the connection of each link is relatively unstable. This indicates that some of the links guarantee lossless communications while the others do not. However, the estimated information sequences, obtained at the destination by decoding the multiple signals, conveyed via the multiple routes, are highly correlated. Hence, even though some links cannot guarantee the lossless communication, it is still possible to recover the transmitted information at the destination with some levels of distortion lower than specified.

Figure 1.3 shows an example of a lossy distributed cooperative network, where there are no error-free tandem connections between the source A and the destination E. This network can be further decomposed into a lossless and a lossy network, as shown in Figure 1.2.

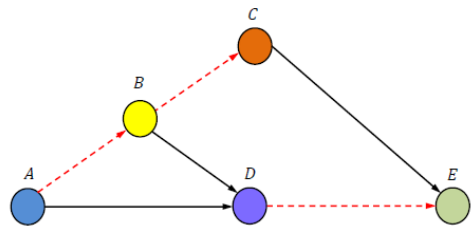


Figure 1.3: An example of a lossy network.

1.2.2 Slepian-Wolf rate region

The theoretical background of the simplest cooperative communication system, one-way relaying allowing intra-link errors, can be related to the source coding theory with side information. An exemplifying block diagram is shown in Figure 1.4. Here, the source aims to transmit the information sequence ***s***, and the destination aims to recover ***s*** with aid of the side information ***r*** provided by the helper. In order to help in the recovery of ***s***, side information ***r*** must be correlated with ***s***.

The encoders at the source and at the helper adjust their *compression rates*, R_s and R_r, with the aim to minimize the signalling load while facilitating error-free recovery of the messages by the decoder. The *admissible rate region* of the source and the helper is shown in Figure 1.5, where notation $H(\cdot)$ denotes entropy of the argument. The rate region for the case of two independent (uncorrelated) sources is shown in the rectangular indexed by "independent".

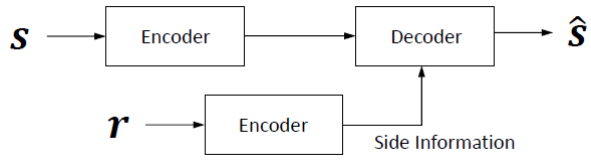


Figure 1.4: Source coding with side information.

The Slepian-Wolf [SW73] admissible rate region for two correlated sources is indexed by A3, where the assumption is that both messages ***s*** and ***r*** need to be decoded. Obviously, it is found that the region A3 is much larger than the case where the two sources are independent, resulting in decrease of the required transmission rates.

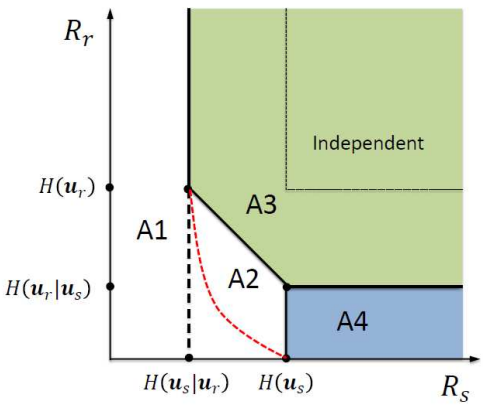


Figure 1.5: Admissible rate regions for Slepian-Wolf system and source transmission with a helper.

When applying the Slepian-Wolf system concept to the simple one-way relay system (shown in Figure 1.2 (a)), the helper's sequence ***r*** is an erroneous version of the original sequence ***s***. Thus, the decoder does not need to recover ***r***. Hence, when viewing the one-way relaying systems from the one-helper Slepian-Wolf theorem, the admissible rate region is the area shown above the red curve in Figure 1.5. This region corresponds to the case where the helper's information (or relayed sequence) is

only used to recover the original source information, and the relayed information does not have to be fully recovered. It is found that, however, the admissible rate region with one helper can be well approximated by the region “A3 plus A4”, when only the source information is intended to be correctly recovered.

1.2.3 Distributed turbo code

As stated before, cooperative communication network can be seen as a distributed turbo code. In this scenario, encoding at each node provides *error protection* instead of compression. On the other hand, the “compression” is induced by the limited radio channel capacity in each link, which restricts the successful point-to-point transmission rate. If the rate set supported by the channels falls within the admissible rate region, the decoder is again able to successfully decode the transmitted data. Here, the boundary of the admissible rate region can be approached by adjusting the transmit powers. In this case, the cooperative relaying provides savings in terms of required SNR.

Since the channel gains change due to fading, the outage for the end-to-end connection happens when the rate pair falls outside the admissible rate region. The average outage probability is the probability averaged over the probability density function of the link gain variations of the links. Furthermore, the link variation property largely depends on the propagation characteristics of the link gains, e.g., the links are composed of none-line-of-sight (NLOS) components only, or some of them contain line-of-sight (LOS) components. When there is no tandem connection having no errors after channel decoding at the nodes (lossy case), the outage calculation is much more complicated. This will be the most challenging part of this project.

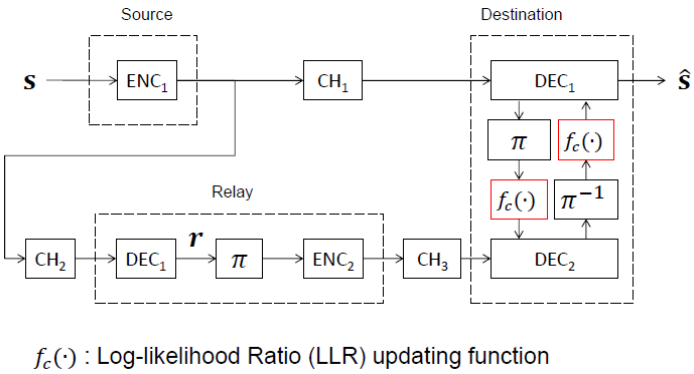


Figure 1.6: A block diagram of the one-way relay system allowing intra-link errors from the viewpoint of distributed turbo code.

A block diagram of the simple one-way relay system allowing intra-link errors, corresponding to the network shown in Figure 1.2 (a), and seen from the viewpoint of a distributed turbo code, is shown in Figure 1.6, where the decoder is shown on the right hand side of the figure. The box “fc(•)” is the LLR updating function that performs the “compensation” of the LLR values due to the limited correlation between the two signals. “fc(•)” utilizes the knowledge of the correlation between the information parts of the signals transmitted from the source and the relay.

This structure, including the whole transmission chain, matches with what the Slepian-Wolf theorem for the correlated source coding states: If the rate set supported by the channels falls into the admissible region, and if the joint decoder at the destination can utilize the correlation knowledge between the information sequences, the transmitters can independently encode and transmit the information sequence, and they do not have to negotiate over the code parameters to be used.

Furthermore, because of the source-channel separation theorem, source and channel coding can also be performed independently, so far as the rate set falls into the admissible region. Hence, the fundamental supporting theory to the “link-on-the-fly” system is lossless/lossy distributed correlated joint source-channel coding, where the signals transmitted from the relays are regarded as helpers.

Analysing the admissible rate region for the lossless transmission may not be intractably difficult, but in lossy case, the complete analysis is expected to be significantly difficult and requires a lot of effort. Furthermore, when the variety of applications such as V2V and group-to-group communications are

considered, the characterization of the change of channel property plays important roles, which invokes the necessity of modelling of the channel property change.

2. Scenarios

This chapter describes potential use case scenarios and communication applications with varying QoS requirements for the RESCUE system. State-of-the-art solutions and standards are also reviewed. The first practical framework for the links-on-the-fly concept is *public safety operations* that take place in areas where the communication infrastructure is partially inoperable due to a disaster such as earthquake. Another potential framework is *vehicle-to-vehicle* (V2V) communication. Here, cars and other vehicles share, for example, safety-critical information about the road and traffic conditions with each other.

2.1 Public safety operations

Crises may happen everywhere in the world, thus a force of intervention must be able to react to any emergency situation, despite of the environmental conditions and their equipment. It is commonly accepted that one of the best ways to ensure a prompt and effective intervention is to provide and maintain cooperation between members of the team, as well as cooperation with external elements such as, for instance, a command and control unit (C2).

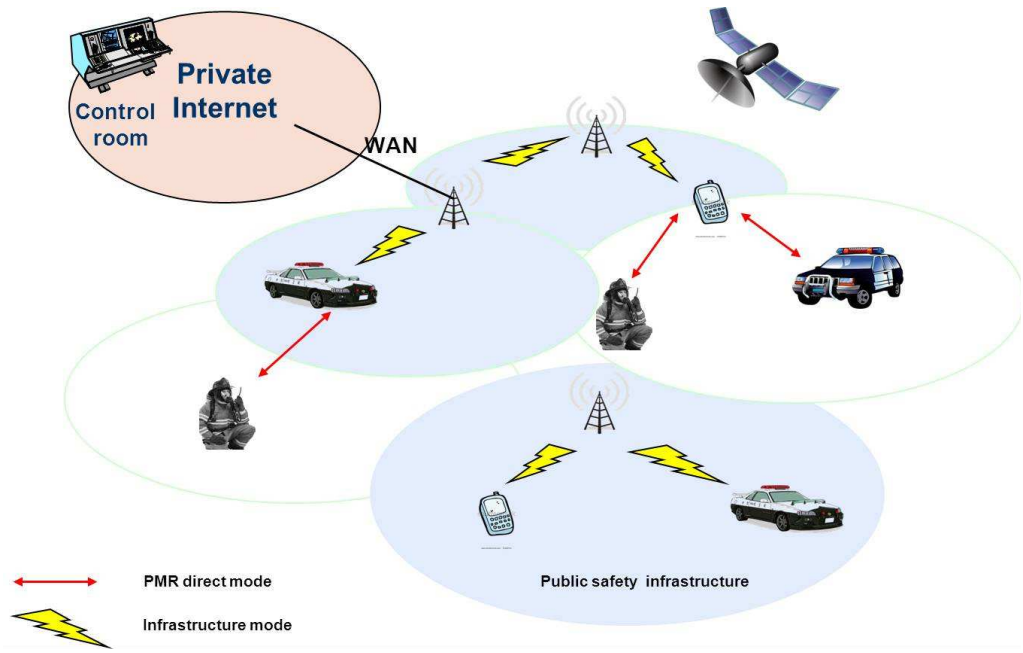


Figure 2.1: Traditional public safety scenario.

In order to achieve the required communication objectives, public safety operators rely on dedicated networks that ensure specific services highlighted in Figure 2.1. In practice, these networks have similarities with civil mobile cellular networks with the main following differences:

- Public safety networks operate on dedicated spectrum bands specifically dedicated for the rescue operations. Indeed Public Protection and Disaster Relief (PPDR) operations exploit the 400 Mhz band in Europe and the 700 Mhz in the US.
- Public safety networks are managed by dedicated operators with the main objective of ensuring high resilience and reliability.
- Most PPDR deployments today are based on the TETRA standard. This standard is very similar to the GSM (2G) standard with a main focus on voice communication and very limited capacity for DATA exchange (refer for TETRA description above).
- The main additional feature introduced for in the TETRA standard is the Direct Mode Operation (DMO). This feature enables device to device communications (monitored by the access point) thus extend the network coverage and access rescuers outside the range of base stations.

- The LTE technology is foreseen as the future PPDR standard in Europe and the US. Public safety providers will operate LTE over the same LTE bands thus offering additional capacities and services during the relief operations.
- With the increase of throughput and the evolution towards an IP based architecture connecting the public safety networks to a command and control C2 will become easier. This will allow a real time management, planning and coordination of rescue operations.

Historically, two main services are required during relief operations by public safety workers. These services are already supported by existing PMR networks since they require limited throughput to operate.

Blue force tracking (BFT) service aims at distributing to all participants in the relief operation the GPS coordinates of public safety workers. This service is achieved through a synchronized network where each worker broadcasts periodically its position that is then conveyed and shared with all other rescuers. Clearly, exploiting the new generation of devices to distribute images, videos, and even voice recording from the scene can be of an extreme importance for rescue workers. These new type of information are even more important and pertinent when coupled to the exact geographical positions of participants (already offered by the BFT classical tracking).

Another service in public safety operations is the **Push-to-talk (PTT)** communication. The PTT allows walkie-talkie like communications between rescuers. It enables only voice point to multi-point communications with limited throughput. This group communication solution is based on a TDMA access technique where a circuit is established to multiple receivers over the same time slot (as shown in the figure below). These timeslots are allocated and released manually by the sender. Clearly, adding to the half-duplex voice communication, video and/or data services can help save lives in a rescue area.

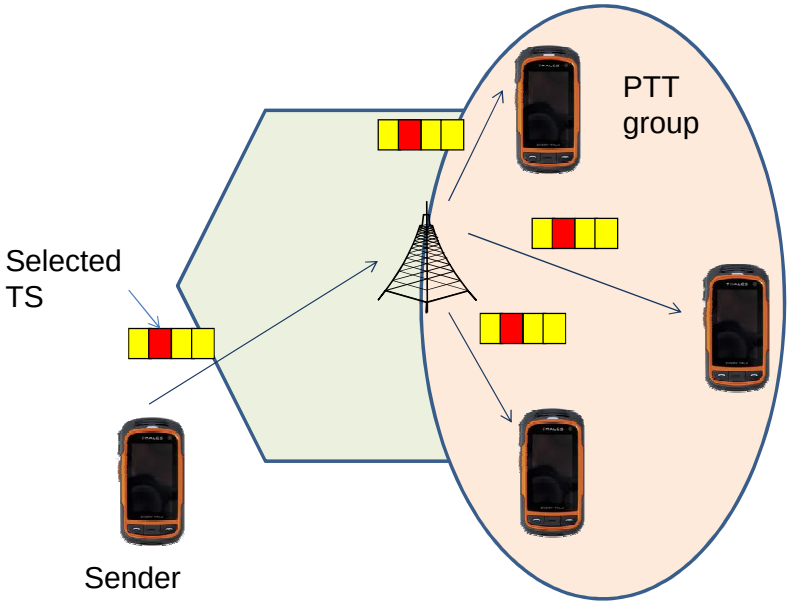


Figure 2.2: Push-to-talk communication.

2.1.1 Common public safety solutions

TErrestrial Trunked RAdio (TETRA) is a digital trunked mobile radio standard developed by ETSI to meet the needs of traditional Professional Mobile Radio (PMR) user organisations such as:

- Public Safety
- Transportation
- Government
- Military
- Oil & Gas

In order to address the particular requirements of PMR users, TETRA implements two main features:

- Wide area group communication i.e. one to many communication pattern
- Direct Mode Operation (DMO) allowing one hop Device to Device (D2D) communications

The TETRA recent specifications [ETR300-1] were developed explicitly to give a multi-media radio platform able to support simultaneous voice, data and image applications to each radio platform. This capability was deemed attractive to the potential market and by incorporating it on to a single radio platform minimized the blocking and intermodulation problems common with other multi-function radios.

The radio access protocol is based on a four slot per carrier TDMA arrangement. The protocol is sufficiently flexible to allow four independent circuit mode applications (i.e. voice or circuit mode data) and/or any number of independent packet data applications to be simultaneously supported, up to the limit of the capability of the radio or the channel capacity of 28,8 kbit/s (gross) 19,2 kbit/s (net).

TETRA radio layer (Air Interface) parameters defined in [ETSI TS 100 392] and [ETSI EN 300 396] are summarized below in Table 2.1 and Table 2.2.

Table 2.1: TETRA infrastructure mode.

Environment	Outdoor
Maximum P_T of the BS	44 dBm
Maximum P_T of the UE	40 dBm
Communication range	4 km – BS to UE
Pathloss model (LOS)	158 dB, h_b BS antenna height, h_m UE antenna height, f_c carrier frequency (Mhz)
Central frequency	380-400 Mhz
Bandwidth	7.2 K – latest standard ~100 K
Antenna gain of the BS	2 dBi
Antenna gain of the UE	8 dBi
Noise figure of the BS	6.4 (Sensitivity -115 dBm)
Noise figure of the UE	9.4 (Sensitivity -112dBm)
EVM requirement	Peak 0.3 per symbol (PI/4 DQPSK)

$$69{,}55 + 26{,}16\ \log_{10}(f_c)\ -13{,}82\ \log_{10}(h_b)\ -\ (1{,}1\ \log f_c\ -\ 0{,}7)\ h_m + (1{,}56\ \log_{10}(f_c)\ -\ 0{,}8)\ + \left(44{,}9 - 6{,}55\ \log_{10}(h_b)\right)\ \log_{10}(R) - 2\left(\log_{10}(f_c/28)\right)^2 - 5{,}4\ [\mathrm{dB}]$$

Table 2.2: TETRA direct mode operation.

Environment	Outdoor
Maximum P_T of the UE	40 dBm
Communication range	~ 1 km – DMO
Pathloss model (LOS)	158 dB, h_b BS antenna height, h_m UE antenna height, f_c carrier frequency (Mhz)
Central frequency	380-400 Mhz
Bandwidth	7,2 Kbits/s
Antenna gain of the UE	8 dBi
Noise figure of the UE	9.4 (Sensitivity -112dBm)
EVM requirement	Peak 0.3 per symbol (PI/4 DQPSK)

$$69{,}55 + 26{,}16\ \log_{10}(f_c)\ -13{,}82\ \log_{10}(h_b)\ -\ (1{,}1\ \log f_c\ -\ 0{,}7)\ h_m + (1{,}56\ \log_{10}(f_c)\ -\ 0{,}8)\ + \left(44{,}9 - 6{,}55\ \log_{10}(h_b)\right)\ \log_{10}(R) - 2\left(\log_{10}(f_c/28)\right)^2 - 5{,}4\ [\mathrm{dB}]$$

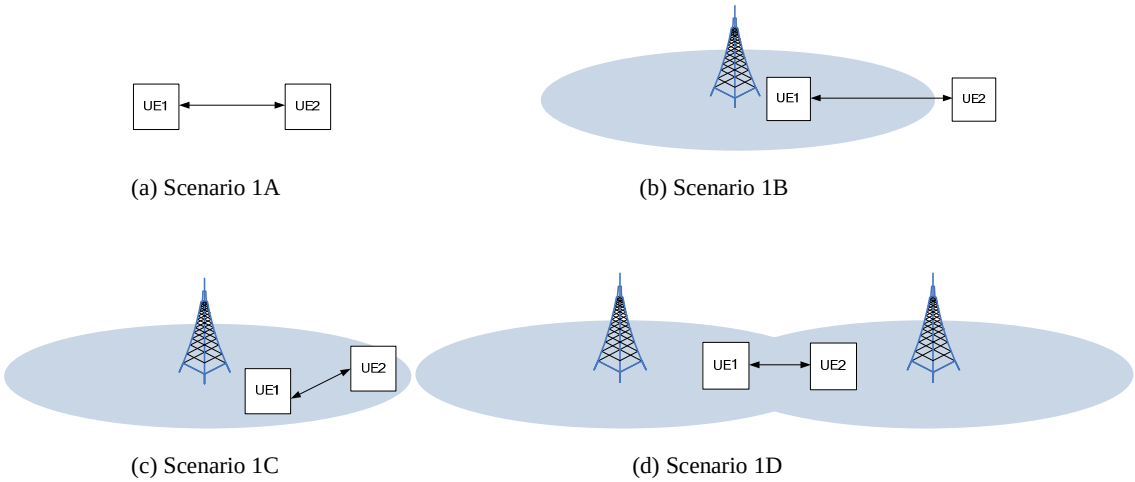
Two separate technology families exist today to provide wireless communication: the commercial cellular networks and dedicated public safety solutions. Today industry and standardization bodies are pushing towards the convergence on a single technology of both families. Considerable efforts have been conducted at 3GPP to include public safety requirements in the coming LTE releases (Release 12). [ETSI-PS].

The main enhancements to the current LTE standards in order to address public safety operations are the following:

- Proximity services that reproduce the direct mode (DMO) enabled in the TETRA standard.
- Group call feature that supports the fundamental requirement for efficient and dynamic group communications operations such as one-to-many calling.

Ongoing discussions today are advocating for the use of LTE technology over the already dedicated public safety spectrum bands. 3GPP is now in the process of designing technical standards to meet the first phase of broadband public safety requirements. Work is still on going to identify and prioritize other enhancements needed for LTE. Both commercial cellular and public safety systems need to be able to survive network equipment failures and overload situations but the requirements for public safety are more rigorous. In June 2013 3GPP agreed to study how to enhance the resilience of LTE networks for public safety applications.

Precise network characteristics are in early phase of specification. They define the proximity services as a single hop network extension as shown in Figure 2.3 below.



(a) Scenario 1A (b) Scenario 1B

(c) Scenario 1C (d) Scenario 1D

Figure 2.3: LTE proximity services.

Table 2.3 below, obtained from the 3GPP technical specification [3GPP TR 36.843], compares the LTE deployment in general LTE and public safety scenarios.

Table 2.3: LTE general and public safety scenarios.

	General Scenarios	Public Safety Scenarios
Carrier Frequency (Note: The performance at 2GHz is expected to be different from the performance at 700MHz.)	2GHz	700 MHz
System bandwidth	10MHz Uplink and 10MHz Downlink for FDD, 20 MHz for TDD	10MHz Uplink and 10MHz Downlink for FDD, 20MHz for TDD for in-coverage and partial coverage scenarios, 10MHz dedicated spectrum for out-of-coverage scenarios
Network operation	100% eNodeBs enabled	0% eNodeBs enabled 100% eNodeBs enabled 3-site clustered eNodeB enabling pattern for 19 cells layout as shown in Figure A.2.1.1-1 for partial network coverage[a]

UE out of coverage criterion	N/A	Average SINR < -6 dB over system bandwidth.
UE mobility (only used for small scale Doppler modeling of channels)	3 km/h	60km/h for outdoor UEs in Option 5. 3km/h for all other cases.
UE RF parameters	Max transmit power of 23 dBm for non public safety, 23 dBm, 31 dBm for public safety 1 Tx (2 Tx optional for public safety only), 2 Rx antenna, Antenna gain 0 dBi, Noise figure 9 dB	
Total number of active UEs[b] per cell area[c]	Indoor-outdoor mix: 25	Indoor-outdoor mix: 10 Uniform (outdoor): 10 Hotspot: 10
Total number of UEs (including active UEs[b]) for discovery per cell[c]	Indoor-outdoor mix: 150	Indoor-outdoor mix: 150 Uniform (outdoor): 150 Hotspot: 150
Number of UEs participating in a D2D communication session	Unicast : 2 Groupcast: N/A Broadcast: N/A	Unicast: 2 Groupcast: 10 (One transmitter UE and 9 (N_{gr}) receiver UEs)
UE association for Relay D2D communication	N/A	First UE is randomly selected from all UEs without eNodeB coverage and 2nd UE is selected from the UEs within eNodeB coverage
Minimum distance between eNodeB and building center[e]	100 m	
Minimum distance between UE and eNodeB	>=35m	
Minimum distance between UEs	>= 3m	
Wraparound	Wraparound is used for all cases except partial network coverage, for which no wraparound is used.	
Minimum association RSRP for D2D communication (X) (baseline)	-112dBm	

2.1.2 Situational model

Nevertheless, in many cases communication links cannot be maintained due to numerous factors. First, in the most common case, rescuers operate outside the coverage range of base stations. Indeed, the higher the distance between communicating entities, the lower the SNR and the higher the loss rate over that link. Second, in some extreme catastrophe conditions, the communication infrastructure can be partially destroyed. The RESCUE project tackles these particular issues by proposing an innovative coding technique for lossy links. These losses can be either caused by long communication distances or the partially destroyed infrastructure. The RESCUE project focuses particularly on the latter case. The focus is on relief operations taking place in urban areas where the rescuers are densely deployed.

In order to maintain connectivity in scenarios where the communication infrastructure is partially destroyed, deployable/mobile base station are usually required. However, such solutions suffer from cost and feasibility drawbacks essentially in hazardous and difficult-to-reach areas. Indeed, deploying on the

fly dedicated trucks carrying base stations is possible today in public safety areas. In some particular catastrophe situations, satellite communication can even be exploited depending on the extent of the event and the participating relief groups. However, offering quick cost effective, and easily deployable communication opportunities in the specific case of partially destroyed infrastructures, difficult to access due to terrain conditions or location, cannot covered by the 2 previous solutions. Consequently, PPDR main actors are continuously looking for "lower cost" communication solutions that can be easily deployed. Indeed, such solutions are of a high importance in public safety operations where the earliest deployed relief efforts have the highest chance of finding survivors and saving lives. Therefore, empowering rescuers with quick, efficient and reliable communication solution constitutes a permanent challenge for actors in this domain.

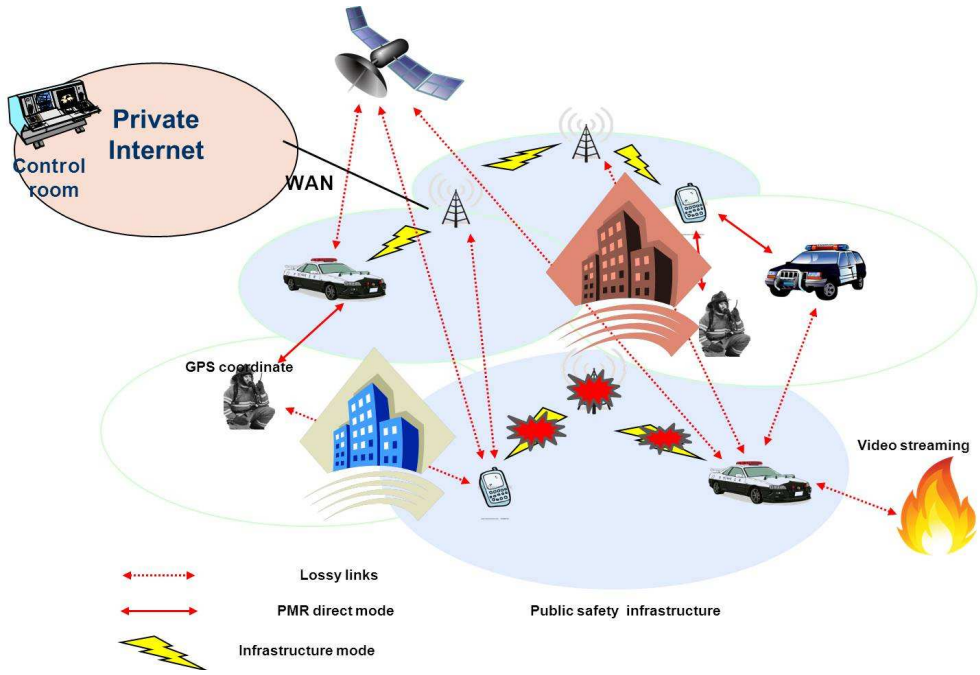


Figure 2.4: Partially destroyed public safety infrastructure.

We show in Figure 2.4 a typical example of a partially destroyed public safety infrastructure. In such situations, a number of access points can be demolished hence rendering a disconnected networks with inaccessible areas. Unfortunately, these inaccessible zones are the most affected areas by the catastrophe where rescuers will operate first requiring communication facilities. These teams interactions are not only intended to manage locally their activities but also to coordinate relief operations of different rescue teams in the control room C2. Besides, in these partially destroyed infrastructures, many lossy links (dashed arrows in Figure 2.4) are available. Such links are usually not exploited in traditional wireless networks since they present high error rates. Additionally, the more rescuers are deployed in the area, the more lossy links are available creating further diversity and routing paths to the operating infrastructure.

Public safety operations usually take place in outdoor circumstances. However, rescuers will need to maintain communication also when entering indoor facilities such as factories, warehouses, or residential buildings, for example in order to carry out search and rescue operations. In this case, the communication channels between the rescue personnel and the control unit suffer from attenuations caused by heavy walls or floors instead of large distances. Furthermore, the movements of the personnel inside buildings will result in significant dynamic changes in the connectivity and the network topology.

2.1.3 Communication case

Following an important infrastructure collapse, a deployed public safety network presents relatively new and highly challenging communication characteristics. We detail herein few technical aspects observed in these types of networks.

- **Channel characteristics**: PPDR deployments usually cover big areas with hundred meters of communication range. Indeed, a TETRA base station creates cell of a radius that can reach one Km. This range can also be extended with the relaying capability of public safety devices (Direct

Mode). Consequently, the communication medium is established between in line of sight nodes. Since the operating frequencies are assumed low and communication distance relatively high, the channel can be modelled as low capacity suffering from shadowing phenomenon. Note here that in an urban operation with a partially destroyed infrastructure, communication ranges tend to increase, favouring additional device to device information exchange thus lower distance device to device communications. It is also worth noting that in some particular cases, rescuers might operate in indoors conditions. This can have non negligible impact on the observed wireless environment as we describe further in this document. .

- **Node density**: Traditionally public safety scenarios are characterized by a reduced number of base stations. Indeed, this is a direct impact of using low frequencies and high transmission ranges. However, in partially destroyed networks in urban environment, exploiting device to device interactions shall increase node density thus changing completely the properties of the studied network. In such configurations allowing more than one hop relaying in the rescuers device becomes necessary. Therefore, going one step further than the actual public safety direct mode (DMO) that enables only a single hop extension from the base station needs to be considered in our scenario. Moreover, depending on the density of our deployments, a diversity of routes between two communicating nodes can be established. Exploring this route diversity can offer considerable advantages in such scenarios

- **Node mobility**: We consider a network topology with fixed communicating nodes. In fact, during a relief operation, it is assumed that rescuers do not move during their communication periods. In other words, this can be formalized as considering rescuers mobility timescale much greater than communication timescale. Note here that we do not consider in our scenario communication with mobile vehicles but only with deployed rescuers in the relief area. Vehicle to infrastructure and vehicle to vehicle communication patterns are considered in other use cases within this project.

- **Traffic pattern**: Most of public safety operations rely on a point to multipoint communication scheme. Indeed, a major part of the information exchanged target essentially the whole group participating in the mission. More precisely, coordination orders from the control room are distributed to the whole rescue teams. Similarly, locally observed conditions observed by individual rescuers are shared with team members. This observation also applies to blue force tracking where coordinates of every single node are of an interest for everybody.

In addition to the blue force tracking and push to talk services, new applications are emerging in the area of public safety. These applications have new constraints and additional requirements that need to be satisfied. We describe below the most relevant applications and quantify their quality of service (QoS) requirements.

- **Blue force tracking** distributes periodically the GPS coordinates of participating rescuers. This application has a point to multipoint traffic pattern. Since these messages are sent at a regular basis, losing an update from time to time is tolerated. Moreover, since the position is periodically refreshed transmitting a delayed BFT message is not necessary. Therefore the BFT service requires tunable reliability and strict delivery delay threshold. In other words, if the intermediate node estimates that the BFT update will not meet a decided deadline before reaching the destinations the updates can be locally dropped.

- **Push-to-talk** is a half-duplex voice application that allows group communication between rescuers. This service requires strict delivery delays since many of the sent voice messages will generate instantaneous interaction between users. As for the loss rate, voice applications tolerate limited error rate because the human brain is able to decode the sent voice message even though part of the information is corrupted.

- **Short message service** is part of the new types of application emerging in public safety area. Clearly typing a message during a relief operation was long time considered as not feasible. Especially that rescuers usually have special gloves resistant to fire, water and tough weather conditions. However, with the latest progress in voice and speech recognition area, it is becoming possible to write sms by simply speaking to the device. Consequently, public safety operators are seriously studying the possibility of adding this feature in public safety devices. The SMS service, requires high reliability in the delivery process (0 error rate at the application layer) but can tolerate few seconds delays.

- **Video streaming service** is also a new service that shall become possible with the new generation of radio communication devices. In fact, the fast evolution in the area of cellular

mobile devices and the widespread of smartphones having very high computing and communicating capabilities is undoubtedly impacting the PPDR domain. Therefore, capturing real time videos and streaming them to rescue teams and even to command and control centre is very seriously envisaged. Such videos will allow better understanding of the situation, deciding whether deployed rescue teams are enough and planning how to coordinate the rescue efforts. In terms of quality of service, video streaming applications are tolerant to losses due to recent progress in video codecs. They can also compensate delays through buffering. However video streaming is very sensitive to jitter. Indeed, since the buffering period is fixed, any variation in the end to end to delay can cause buffer overflow or buffer starvation at the receiver.

Table 2.4 below summarizes envisaged public applications with precise QoS requirements in a public safety deployment.

Table 2.4: QoS requirements for public safety applications.

Application	Size	Throughput	BER	Delay	MAC layer
SMS	200 Bytes	2 Kbits/s	Close to 0 after correction	Seconds	CSMA
Video stream	90 – 240 Bytes	64 kbits/s	10^-2	Seconds (buffering with low jitter)	CSMA like
Sensor data	50 Bytes	Few Kbits/s	10^-2	Updates every 10s	CSMA
BFT	80 bytes	128 Bits/s		Every minute	TDMA
PTT	Variable	14,2 Kbits/s	10^-2	22.5 ms (interactive)	TDMA

2.1.4 Wireless characteristics

In the public safety use case mobile network nodes are encouraged to create an ad-hoc network with a limited access to a working base station or other infrastructure. Due to dense deployment of rescuers and mobile devices in general, low distances between the nodes can be assumed and each node will only communicate with its close neighbors. Also a low quality channel can sometimes be assumed to reach remaining base stations. Mobile network nodes are either end-devices of the rescuers working in the destroyed region or mobile base stations deployed stationary or on top of moving trucks. Due to high population density in industrial countries mostly the devastated regions have urban character with many buildings of varying height and streets of different widths, crowded with cars and trucks, traffic lights, and traffic signs.

The moving speed for rescuers that operate afoot can be safely assumed to be below 20 km/h. The mobile base stations in an urban area will also be assumed as deployed in fixed positions. Furthermore, in a densely deployed rescue area, the distance between the nodes is assumed to be below 100 m and the urban character of the region creates severe multipath echoes in the wireless channel with or without line-of-sight (LOS) connections between the nodes. Therefore the B1 and B2 channel models of the WINNER 2 project are considered for these scenarios. A typical channel impulse and frequency response of the tapped delay line model is shown in Figure 2.5. An overview of the underlying physical channel parameters is shown in Table 2.5. The contained values are calculated from the B1 (Urban micro-cell) and B2 (Bad urban micro-cell) channel models that were provided by the WINNER 2 project [WIN2D112] where an average node distance of 100m was considered. It is worth noting that the WINNER models apply to frequencies between 2 and 6 GHz, and thus should not be used for evaluation in the 700MHz band. In the RESCUE project, the focus is on carrier frequencies above 2 GHz.

Table 2.5: Physical parameters of the wireless channel.

	WINNER B1 (LOS)	WINNER B1 (nLOS)	WINNER B2
Terminal Speed	0-70 km/h	0-70 km/h	0-70 km/h
Doppler Spread	~50 Hz	~50 Hz	~50 Hz
Coherence Time	17 ms	17 ms	17 ms
RMS Delay Spread	36 ns	76 ns	480 ns
Coherence Bandwidth	5 Mhz	2.6 MHz	417 kHz
Fading Model	Rician and Rayleigh	Rayleigh	Rayleigh
Average pathloss	81dB	81 dB	81 dB
Shadowing	Log-normal, σ=4.7dB	Log-normal, σ=6 dB	Log-normal, σ=6 dB

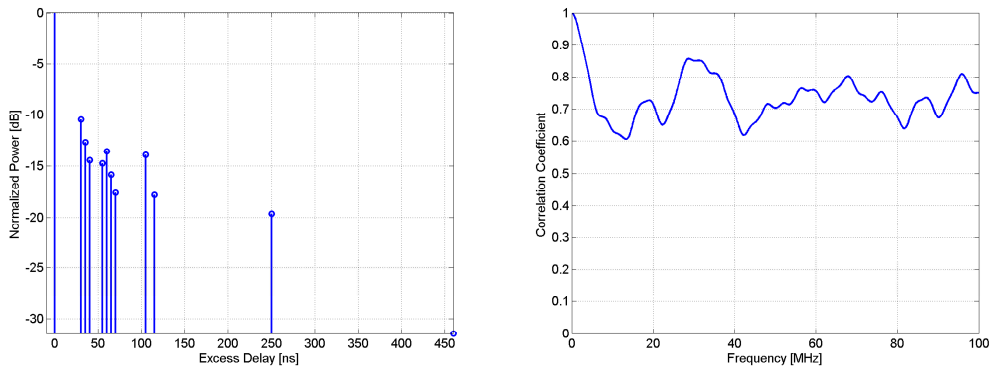


Figure 2.5 Typical channel impulse response of the wireless channel (WINNER B1-LOS) [WIN2D112].

An important part of the concept of the links-on-the-fly technology is the continuous change of the network topology and of the nodes available for communication. From a use case perspective this topology change is mainly coming from the mobility of the distinct nodes that are included in the network. As the rescuers move inside the relief region, LOS connections may or may not be blocked by occurring obstacles such as walls or cars. Furthermore, when rescuers enter an indoor environment, for example a burning house, at least LOS connection is lost, but also links may become unreliable or even drop completely because of the large pathloss or strong scattering. Here, the RESCUE approach will help to keep the communication stable by exploiting several routes in parallel.

Topology changes can also occur when the distance between nodes increases so that only a lossy link or even no link at all can be established. On the other hand, new links become available when two nodes come closer to each other. Additionally, in case of setting up or removing a mobile base station, several links are established or removed. A network topology change can also occur if the wireless resource that was used for one link is used by another, more important link so that the original link needs to be dropped. Essentially, every change in the quality of a node-to-node link can cause a severe topology change that needs to be recognized and handled by the ad-hoc network and the applied coding.

2.2 Vehicle-to-vehicle and group communication

Vehicular ad hoc networks (VANETs) are of paramount importance for providing safety-critical and commercial road services. Many governmental, industrial and academic research activities have been carried out to accelerate the VANETs deployment, so as to provide wireless communications among the vehicles and between vehicles and the road-side infrastructure. Here, the network is a combination of ad-hoc and infrastructure based subnets. In this network each vehicle can be treated as a specific node. Vehicle-to-Vehicle communications (V2V) bring the promise to improved road safety and optimised road traffic through co-operative system application especially for emergency communication scenario analysed in the RESCUE project.

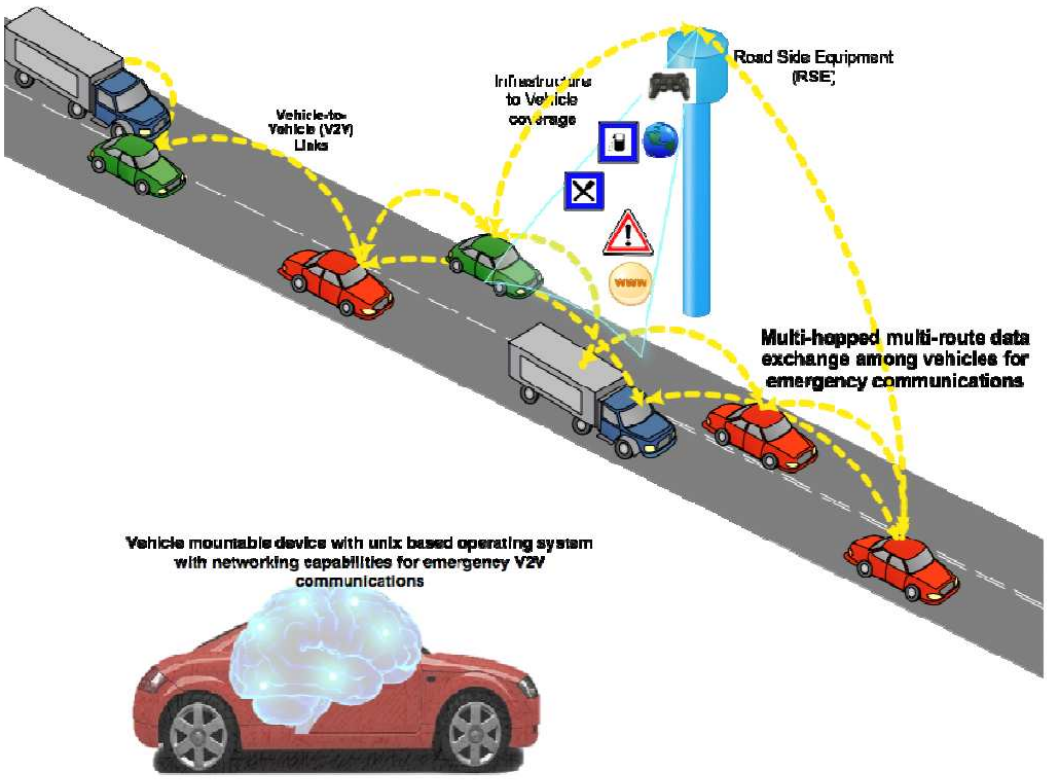


Figure 2.6: Typical VANET architecture with moving nodes.

In the United States the Federal Communication Commission (FCC) allocated 75 MHz of bandwidth in the 5GHz spectrum to dedicated short-range communications (DSRC) contributing to the deployment of the vehicular communications. The European Conference of Postal and Telecommunications Administrations (CEPT) allocated a 50 MHz bandwidth in Europe. The allocated spectrum covers multiple channels, to support cooperative Intelligent Transportation Systems (ITS) for road safety, traffic efficiency and infotainment applications.

The vehicular environment has some unique characteristics, such as the variable and unstable nature of wireless links, the lack of central coordination, the short-lived intermittent connectivity and the dynamic topology that lead to a very challenging multichannel coordination, access and synchronisation. So, the efficient and effective usability of a multichannel architecture is a controversial subject. The communication is achieved by using single-radio or dual-radio transceivers. Single-radio transceivers operate on only one radio channel at a specific time in contrast to dual-radio transceivers that can operate on two radio channels simultaneously [CM13].

Research and application development in VANETs are driven by an amendment to IEEE 802.11 (or ITS-G5 as the equivalent in Europe) to support the cooperative ITS applications where reliability and low latency are crucial.

Table 2.6: Multichannel VANET standards: United States vs. Europe [CM13].

	Europe	United States
Environment	Outdoor (Highway, Urban, Suburban)	Same
Maximum PT of the MT (Mobile Terminal)	Usually 33dBm but up to 44.8 dBm	Same
Central frequency (EU)	ITS road safety: 5 875 MHz to 5 905 MHz ITS non-safety applications: 5 855 MHz to 5 875 MHz	5.85–5.925 GHz
Bandwidth	Total allocated spectrum: 50MHz (30 MHz are reserved in the ITS-G5A band for road safety services, 20 MHz in the ITS-G5B band are for general-purpose ITS services (e.g., road efficiency, service announcements, multihopping))	75 MHz
Channel	4 (CH172, CH174, CH176, CH178)	6 (CH172, CH174, CH176, CH180, CH182, CH184)
Physical and MAC layers	Multiple access technologies, among which ETSI ITS-G5, same as 802.11p	IEEE 802.11p, 1609.4
Higher layer	ETSI ITS Station: Facilities, Networking and Transport, Security layers	IEEE 1609.0, 1609.2, 1609.3
Standard deviation shadowing	2.95 to 2.12 dB 4.49 to 3.55 dB	

2.2.1 State of the art: standards for multichannel VANETs

The standardisation path for VANETs is very complex and it is still being under development even though standard protocols have been introduced. Recently a new protocol standard for vehicular communications has been introduced and adopted. The IEEE 1609 protocol stack known as Wireless Access in Vehicular Environment (WAVE) defines the protocol used for the DSRC as well as the specification for the technical requirements. This new protocol standard includes several technical issues and limitations, such as multi-channel organisation, spectrum allocation, networking and transport design, access layer specifications, network topology, spectrum-bandwidth allocation and applications' requirements specifications. Figure 2.7 describes the protocol architecture developed by the European Telecommunications Standard Institute (ETSI) and the Institute of Electrical and Electronics Engineers (IEEE). The picture is referred to as the IEEE Wireless Access in Vehicular Environment (WAVE) and the ETSI ITS Station [CM13].

Table 2.6 summarises the two standards, which have some common design choices, but they differ in other decisions, for instance, related to the number of service channels.

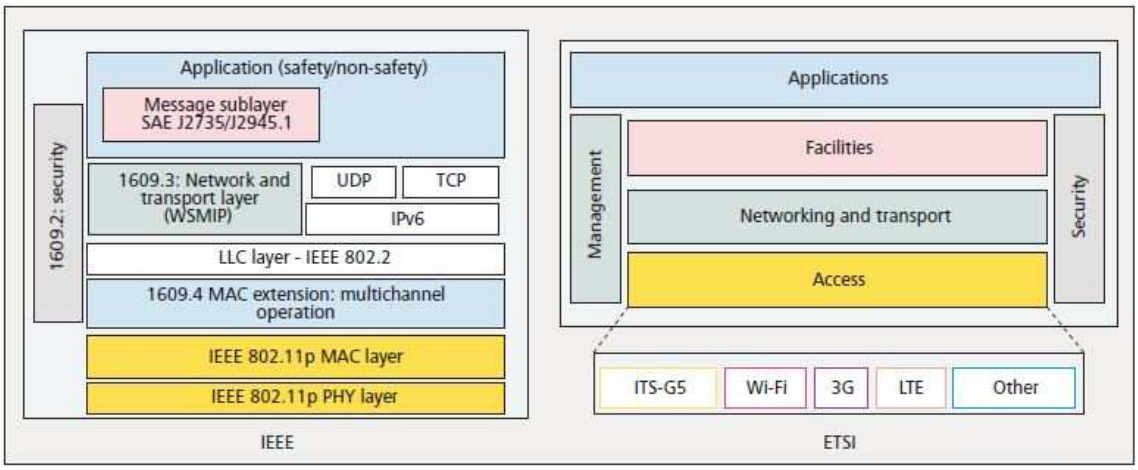


Figure 2.7: Left side: IEEE WAVE stack; Right Side: ETSI ITS station [CM13].

The network perspective of VANETs consists of the physical (PHY) layer, the medium access control (MAC) layer and the network layer. According to IEEE 802.11p, which is not a standalone standard but it is intended to amend the IEEE 802.11 standard, the physical layer involves issues concerning channel and frequency allocation, transmit power control and receiver performance. The role of the MAC layer is to achieve reliable medium access control and to avoid traffic collision. Both physical PHY and MAC layers include management entities, which are called physical layer management entities (PLME) and MAC sub-layer management entities respectively. The role of these management entities is to services interfaces so as to layer management functions to be invoked (IEEE Std 1609.4, 2011). The network layer is related to wireless multi-hop communication which is based on routing and geographical addressing. The purpose of the IEEE Std 1609.3 (2010) is to offer data services and addressing support in a WAVE system.

2.2.2 Situational model and network characteristics

As detailed earlier, the communication in VANET raises several new challenges. Indeed, ensuring end-to-end connectivity in this type of highly dynamic and unstable networks is difficult to achieve with traditional communication and networking techniques. Indeed vehicular networks suffer frequent disconnections, topology changes due to the arrival and exit of new vehicles in the system. Moreover link qualities are highly dependent on distances between cars and their respective speeds thus continuously changing in time. Figure 2.8 lists some characteristics and typical functionalities of VANETs. However, the dynamic and highly unpredictable variations motivate the need for a new generation of communication paradigms for VANET.

We consider in our RESCUE VANETs scenario vehicles equipped with radio-enabled devices, which act not only as mobile nodes but as routers for other nodes too. The portable devices are IP-based as well as having both ad-hoc and infrastructure modes IEEE 802.11 and IEEE 1609 connection capabilities e.g. in-vehicle Linux based mini-laptops or smart phone devices based on Android and iOS.

In terms of features, the mini laptops inside vehicles should be equipped with long range Wi-Fi interfaces (plug-in cards or external vehicle fitted antennas) that will allow them to connect to the IEEE 1609 (WAVE) networks in both infrastructure mode (long connection range required) and ad hoc mode (a second interface required for short-mid range connections).

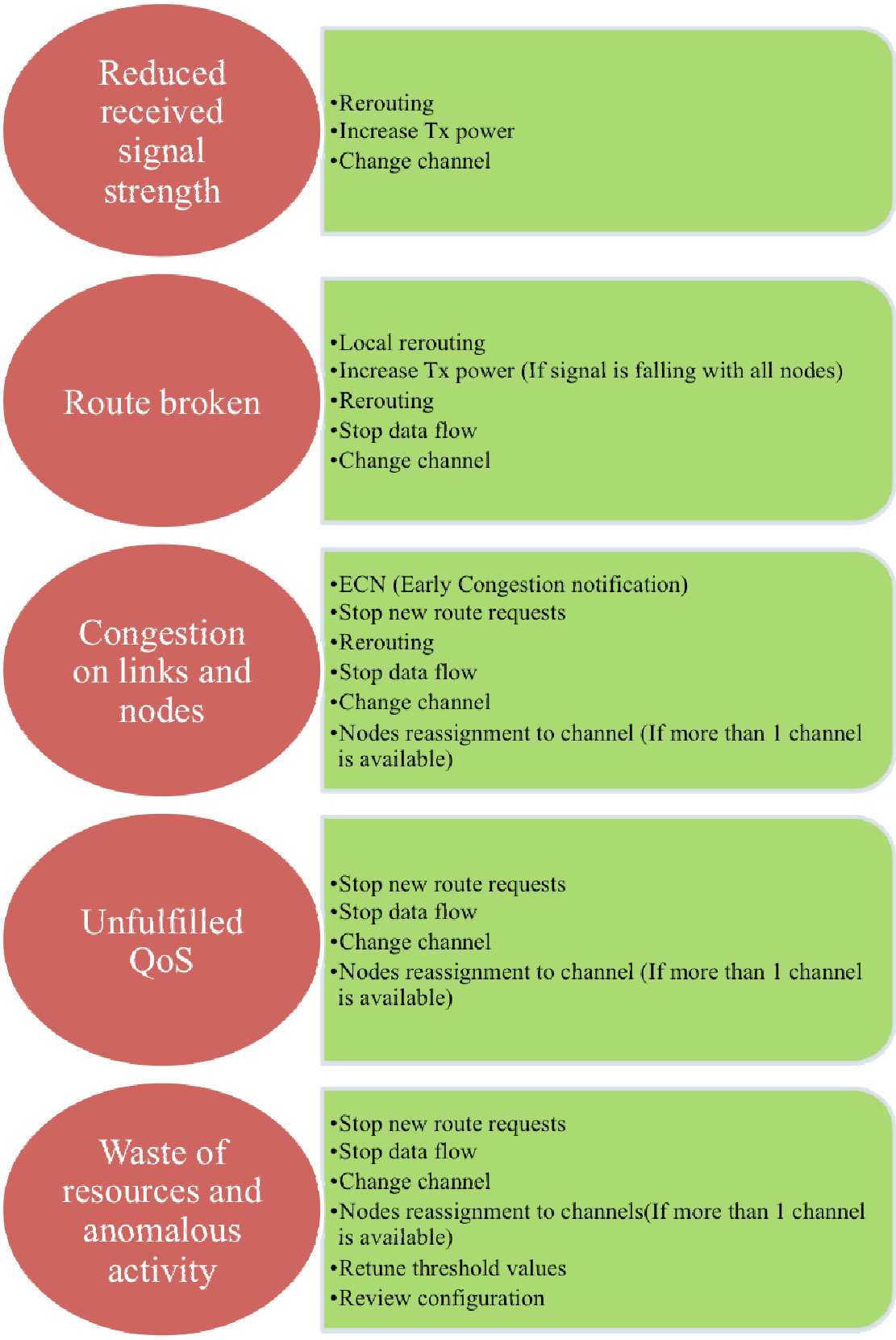


Figure 2.8: VANET characteristics.

In the considered V2V wireless multi-hop scenario the network will be composed by multiple devices. In this context, the objective is to establish point to point communications (voice/video) between two cars (Figure 2.9) as well as distributing road specific messages and advertisement in a point to multipoint

fashion [PA12]. The destinations of the latter communication pattern can be located in a particular area or sharing particular traffic conditions.

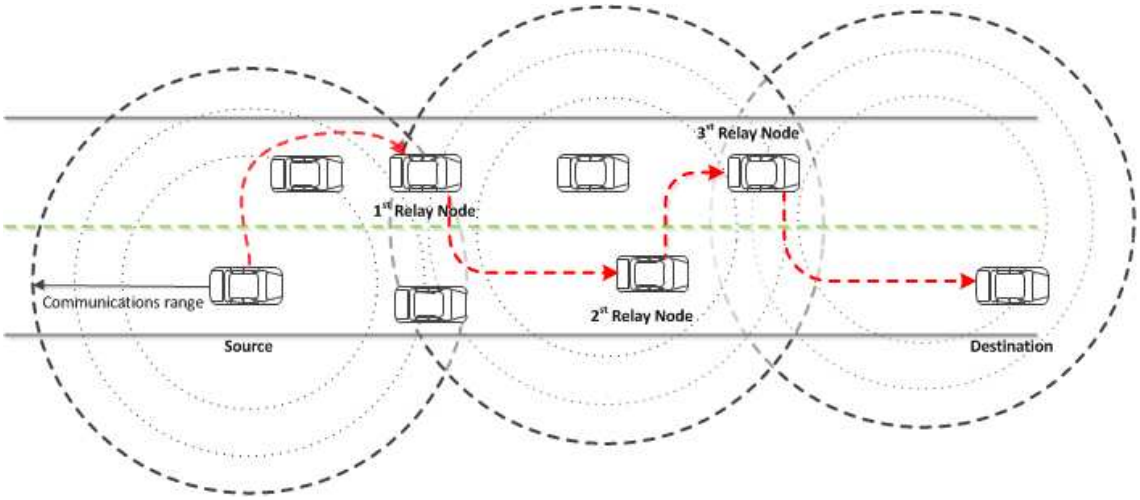


Figure 2.9: Point to Multi-hop message propagation in VANETs.

Figure 2.9 shows that each one of the vehicles (nodes) has a certain transmission range. Hence, to disseminate the information to each one of the nodes, the message has to be transmitted to a node which is within the sender's transmission range (first hop), then the node that received the message has to send it to the next node (second hop) and so on. If we add the commonly admitted observation that link quality and also relaying nodes are changing in time, achieving robust communications (i.e. establishing the end to end paths) becomes highly challenging.

- **Topology dynamics**: Due to the fact that the vehicles move with high speed, the VANETs topology is not stable, but always changing. These changes can be produced at link level in terms of loss ratio or at neighborhood (topology) change.
- **Topology disconnections**: Because of the aforementioned reason, the VANETs connectivity can change frequently. More specifically, there is high probability of network disconnection when the density of the vehicles is low.
- **Mobility prediction and modelling**: Because of the dynamic topology and the highly mobile node movement, prediction and mobility model are very important for the design of network routing protocols for VANETs. Furthermore, the movement of vehicular nodes is usually constrained because of roads and streets, so if the speed and the street map are known, a prediction of the future vehicle's position can be made.
- **On-board sensors interaction**: Each one of the vehicular nodes is equipped with on-board sensors for providing useful information related to routing purposes and communications links. For instance, GPS receivers are widely used so as to give information related to vehicles' location.
- **Multiple communication environments**: Two typical communications environments are usually considered in VANETs. The first one is the city scenario. There are intersections, buildings, trees and many other obstacles that separate the streets in a city, so it is not always possible to have a direct line of communication between the mobile nodes. On the other hand, in highway traffic conditions, the communication environment is less complex and straightforward, for example constrained one-dimensional movement.
- **Quality of Service (QoS) Support**: QoS is used for safety applications and it can be provided for network applications with two ways: i) by behavior adaptation (from the viewpoint of the application) and by resource reservation (from the viewpoint of the network). The benefit of supporting QoS is that the system behavior can be controlled, resulting to better results with regard to requirements on various performance parameters (e.g. path-loss, delay).

According to Kumar *et. al*. [KKK11], VANETs consist of particular features, such as: distributed processing and organised networking, a highly variable and constrained topology, a large number of nodes including their speed and their distribution, frequent partition because of the high level of mobility,

communication conditions and mobility patterns and low power constraints. Hence, one of the most important features in the field of VANETs is the routing protocol. The term routing refers to all the implemented processes, so as to discover and advertise paths from one point to another and to actually transfer packets between these two points whenever is necessary.

2.2.3 Special communication applications

In addition to classical point-to-point communications between vehicles, we consider in our V2V scenarios some specific VANET applications.

Cooperative collision warning: The objective of this application is to raise cooperative warning in case of a sudden stop of the front car.

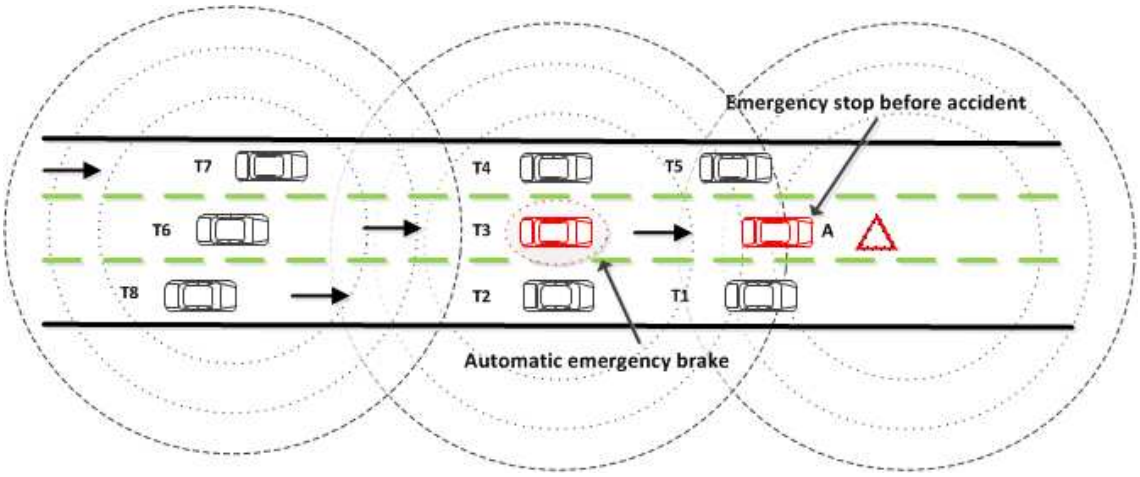


Figure 2.10: Reaction of T3 (emergency brake) due to the sudden stop of vehicle A.

In case of an emergency event, vehicle A has to stop suddenly. That means that all the nearby vehicles (T_1, T_2, T_3, T_4, T_5) are put in potential danger. Very shortly, T_5 and T_1 will pass A so the emergency warning does not concern them. Meanwhile, the vehicles T_6, T_7 and T_8 may get closer to A and have to be informed about the emergency situation.

The major challenge in this case is that low latency in the delivery of emergency messages has to be achieved. Cetin and Jordan [CJ12] proposed a protocol including techniques for emergency warning dissemination, service differentiation mechanisms, and congestion control policies. According to the simulation results, the suggested protocol managed to achieve efficient bandwidth usage in various road scenarios and low latency in delivering emergency warnings.

Making way for emergency vehicles: Yang *et. al*. [YLV+04], presented a strategy that helps the navigation of emergency vehicles through congestion at signalized intersection to be performed with a more efficient way. Their proposed strategy includes communication control messages which are sent to vehicles so as to change their behavior, helping the emergency responsible car (EV) to navigate through congested intersections as fast as possible. This is achieved by splitting the vehicular queue, on one of the traffic lines, at a critical point in order the EV can navigate at its highest speed and at the same time the disruption to the rest of the traffic is decreased. The critical point is determined with the help of the kinematic wave theory (shockwave theory). Figure 2.11 illustrates the case of making way for the EV in a single queue.

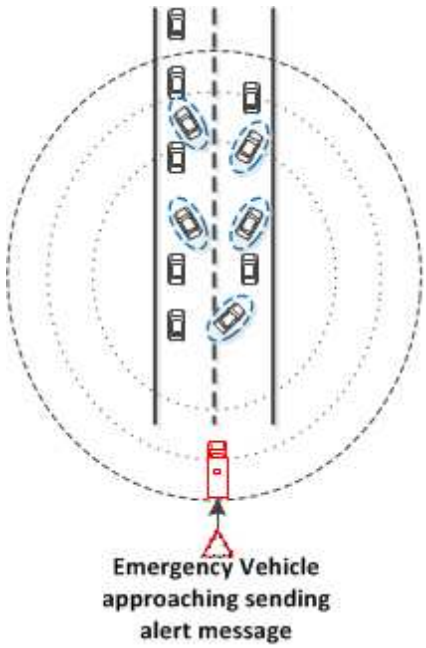


Figure 2.11: Shockwave approach at a traffic light (single queue).

In the case that an emergency vehicle has to pass through a congested road, the vehicles at the other lane must stop at a downstream point from the emergency vehicle so that the lane clears. Hence, the EV can switch lanes at the highest possible speed. The simulation results showed that this strategy can significantly shorten the trip times for emergency vehicles. We also consider this application in the RESCUE project. We study the problem from a different angle by focusing on the physical layer communications and the multi-path routing solutions that enable communication with car along the vehicular queue.

Sharing traffic conditions: Informing other cars with traffic conditions such as traffic jams, car accidents or major events allows authorities to manage traffic and reduce jams and possible accidents on the road. In these applications distributing conditions and alternatives paths to moving cars is necessary. To do so, multihop communications need to be established over unstable and highly dynamic network topologies.

Targeted advertisement: An additional application that is of a high interest for road and highway management is to distribute specific ads to specific users. Based on the history of the car behavior (followed roads, stops etc.) it might be interesting to push a particular type of information to these users. Therefore, this type of application requires point-to-point or even point-to-multipoint (for social groups) communication patterns. It is also spread across very high distance networks suffering from all the drawbacks of wireless multi-hop networks.

2.2.4 Wireless characteristics

In V2V communication scenarios due to the possible high speed of the terminals a fast changing environment must be assumed. In fact, this mobility is the main difference between the public safety scenarios and the considered V2V environment. Accordingly, a wireless communication system needs to be able to cope with high Doppler spreads and fast changing channel conditions. LOS connection between adjacent cars can be mostly assumed, however, when communicating with farther away terminals the LOS assumption is almost impossible to hold. Links between terminals and infrastructure, such as traffic lights, are assumed to have a LOS connection due to the higher position of the access points.

For very high mobility as in V2V, the well-known WINNER channel model [WIN2D112] provides the scenario D1-rural macro-cell. In this scenario, terminal speeds of up to 200km/h are supported, however under the assumption of large cells with LOS conditions to the base stations and low delay spreads. It must be assessed if these conditions are applicable to the V2V scenario also. A sample channel impulse and frequency response is shown in Figure 2.12 and typical values for the physical parameters of the WINNER 2 model D1 are shown in Table 2.7, assuming an average node distance of 100 m. Additionally

B1 and B2 from WINNER can be applied as the channel models also for V2V scenarios, when the mobility is below 70km/h as is the case in urban areas. These channel models will be used in the beginning of the project phase. As the final step, the channel models derived from the measurement of actual V2V channels from WP4 will be applied for more sophisticated analysis.

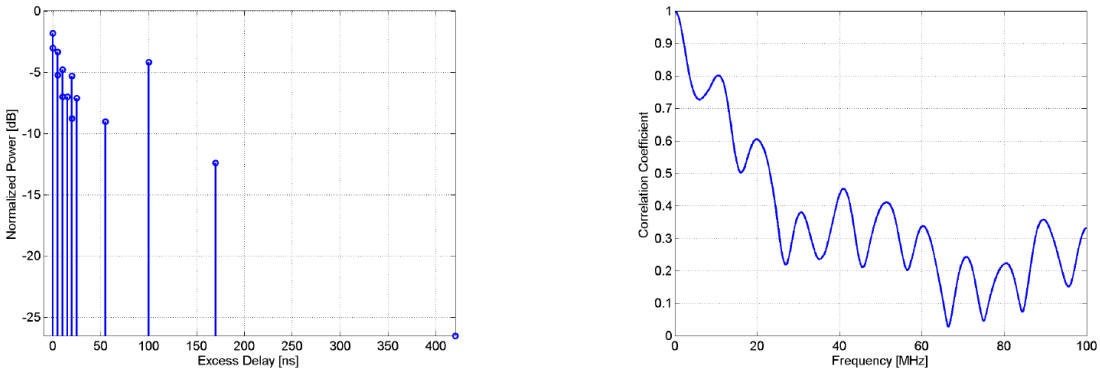


Figure 2.12: Sample channel impulse and frequency responses for WINNER channel D1 [WIN2D112].

Table 2.7: Physical parameters of wireless channel.

	WINNER D1 (LOS)	WINNER D1 (nLOS)
Terminal Speed	0-200 km/h	0-200 km/h
Doppler Spread	~144 Hz	~144 Hz
Coherence Time	5.8 ms	5.8 ms
Delay Spread	16 ns	37 ns
Coherence Bandwidth	12.4 Mhz	5.4 MHz
Fading Model	Rician and Rayleigh	Rayleigh
Average pathloss	82dB	82 dB
Shadowing	Log-normal, σ=6 dB	Log-normal, σ=9 dB

In a V2V scenario, due to the high mobility, the network topology changes occur even more frequently. The change between LOS and nLOS connection between two vehicles can easily appear in case a third car comes into the way and blocks the LOS link. LOS is also lost when one node turns around a corner of a building. Changes of the link quality mostly occur due to the distance change between the nodes but can also happen in case deep fades of the link appear due to the surrounding environment. Finally, establishment and release of wireless links is mostly due to the mobility of the nodes and the change of distance between them.

3. Functional requirements

This chapter details some of the necessary network functionalities of the RESCUE system. The challenges set by the multi-hop communication in the presence of dynamic channel variations and topology changes – for different protocol layers, from physical to network layer – are presented, and some promising protocol design choices are discussed. The key requirements that are distinctive to the RESCUE system are summarized in Table 3.1. In the protocol design, two different cases will be addressed: centralized and synchronized control for infrastructure-based multi-hop networks, and decentralized control for ad hoc networking.

One distinctive difference between communication via the cellular network infrastructure and a fast emergency network roll-out is that, in the latter, the destination may be multiple wireless hops away from the originating transmitter. That is, the network nodes need to receive data packets, and then forward them to the next nodes in the selected route. Furthermore, the nodes may be constantly moving, especially when they are vehicular, which results in constantly changing channel conditions, and – in larger scale – network topology changes.

3.1 Physical layer

The philosophy of the RESCUE communication system is to facilitate safety-related information dissemination in unpredictable environments and somewhat unplanned network topologies. Thus, it is natural that the main aim is to find solutions that achieve reliability and robustness for end-to-end communication applications.

3.1.1 Channel coding and decoding

The foreseen solution for the multi-hop communication lies in a coding scheme where also the erroneously decoded packets can be re-encoded by the relay nodes in a way that the destination can utilize them. The underlying idea is that the destination combines multiple differently encoded copies of the packet via iterative decoding that may correct the errors that were made by the relays. Thus, transmissions do not go to waste even if they are received over lossy links. On the other hand, as it is not a strict requirement that relay nodes need to decode without error, potential relay nodes can be found within a larger radius from the transmitter than when using conventional decode-and-forward relaying. Looking it from the fundamental results of the relay channel, the approach can be interpreted as one smart realization of estimate-and-forward relaying.

An integral feature of the proposed links-on-the-fly communication network will be multi-route relaying. This increases the probability that at least one of the selected routes from the source to the destination has adequate quality, and, thus, the destination is able to exploit link or route diversity. On the other hand, multipath routing makes use of the broadcast nature of the wireless channel: multiple receiving nodes can capture a single transmission and then forward it.

Figure 3.1 illustrates an example of the operation of multi-route relaying on a high level. An essential aspect of the encoding strategy is that each of the encoders – at source and at the relay nodes – are simple serially concatenated turbo encoders that allow iterative soft-in soft-out decoding. Together, the component codes and the network itself form a large turbo code where the component codes are concatenated in parallel. To this end, it is vital that the different encoders employ different internal interleaving orders, which facilitates beneficial information exchange between the component decoders in the destination.

The possible decoding errors at the relays pose additional challenges to the decoder design at the destination. For the benefit of the decoding result, the final decoder should have an idea of how reliable the decoding result at each of the relays was, for example, in terms of information bit error rate. Estimation of the bit error probabilities may be embedded into the iterative decoding process as proposed in [HZA+13], just by comparing the soft log-likelihood ratio (LLR) bit decisions given by the component decoders. As an alternative, already the relay itself may evaluate the reliability of its decoding result, and attach this information to the forwarded packet as overhead.

The scenario of Figure 3.1 becomes more general when more nodes are added to the network and when the destination lies behind more than two wireless hops so that the topology becomes a mesh network. In

this case, also the relaying nodes may combine multiple received packets via iterative decoding before forwarding them. In complex networks, relay selection or routing decisions are needed before packets are forwarded. The routing problem becomes even more elaborate in the case of broadcast applications, where every node is potentially both a relay and a destination.

Finally, ensuring error-free end-to-end connections may be wasteful especially for applications such as live video-streaming, where certain level of distortion is acceptable. A trade-off between distortion and the use of wireless resources can be found by optimizing, for example, in terms of transmit powers and source data rates, according to Shannon's separation theorem which holds both in lossless and lossy cases.

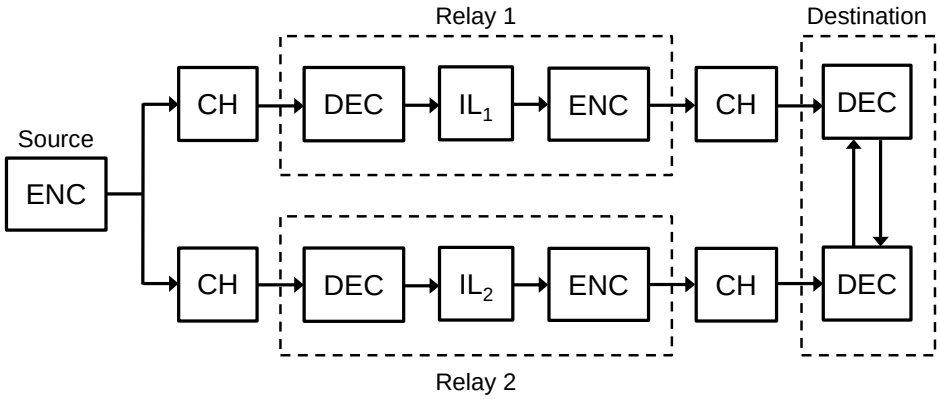


Figure 3.1: Multi-route relaying.

3.1.2 Wireless access and multi-antenna transmission

The main scope of RESCUE project is in source and channel coding and routing, and these issues remain essentially the same regardless of the modulation, channel access, and possible multi-antenna transmission methods employed. Thus, the RESCUE system functionalities can in principle be built on top of diverse technology frameworks, such as TETRA, LTE, or Wi-Fi (IEEE) standards. However, it is also recognized that by designing wireless access and multi-antenna techniques to specifically match the links-on-the-fly concept, additional gains will be obtained in terms of spectral efficiency and reliability. In the RESCUE scenarios, relatively difficult wireless channels with both time and frequency selectivity must be supported. Furthermore, strict synchronism between all the nodes will not be feasible at all times.

In unpredictable environments where proper operations of the network cannot be guaranteed as in devastated areas or densely loaded moving nodes environments, it is impossible to keep interference management and synchronism among communicating nodes. Therefore, physical-layer wireless access and multiple antenna techniques have to be designed satisfying the following requirements:

- Robustness against frame-wise asynchronism
- Robustness against carrier frequency offset (CFO)
- Simplicity of the relay device for low power consumption
- Flexibility in heterogeneous transmission setup.

In this respect, non-orthogonal waveforms such as generalized frequency division multiplexing (GFDM) and/or interleave division multiplexing/multiple access (IDMA) are potential candidates for consideration.

In particular, GFDM is originally developed for cognitive PHY in fragmented white spaces [FKB09]. Unlike OFDM having rectangular pulse shaping, here in GFDM, we have an added flexibility of choosing a suitable pulse, such as Root Raised Cosine (RRC) or Raised Cosine (RC). This pulse shaping technique brings the advantage of extremely low out-of-band radiation of the opportunistic signal into the incumbent legacy band, as RRC pulses have lower side lobes compared to rectangular pulses in OFDM. Moreover, GFDM employs fewer subcarriers compared to OFDM, and thus offers lower PAPR than OFDM. As shown in [MKL+12], GFDM can achieve good performance with simple equalization schemes, demanding reasonable complexity increase in the equalizer.

3.1.3 Multi-rate support

Another design target, competing with reliability and robustness, is spectral efficiency, which translates to higher data rates under given channel conditions. Spectral efficiency can be obtained via rate adaptation, where the transmit data rate is matched to the prevailing conditions. Rate adaptation is also needed in order to support a variety of communication applications that may have different rate or throughput requirements. Traditionally, rate adaptation is realized via multi-rate channel coding and adaptive modulation schemes.

The RESCUE system shall be able to adapt the data rates by means of code rate adaptation and modulation order selection. Different modulation orders, such as QPSK and 16QAM, set different limits to the maximum data rate. The interplay between the modulation order, code design, and modulation mapping rules need careful design in order to guarantee the convergence of the iterative decoder in the receiver side.

3.2 Data link and network layers

The data link and network layers of today's wireless communication systems are optimized for data communication using either single or multi-hop transmission. This requires the lossless exchange of data at each consecutive hop along the data path. Usually, the lossless exchange is assured by error detection and (optionally) error correction techniques. If unrecoverable errors occur, appropriate retransmission procedures are invoked. In contrast to this approach, the RESCUE transmission system embraces the existence of erroneous frames and allows for multiple copies of the same data frames, differently coded at the PHY layer, to be sent over multiple routes. Therefore, in the area of message transfer significant progress needs to occur in three major areas: data link layer (design of MAC, ARQ, and multi-rate protocols), network layer (design of an adaptive routing protocol), and design of cross-layer node coordination methods.

In order to efficiently use the wireless resources and provide appropriate services in unpredictable environments, all protocols for lossy distributed communication need to effectively utilize the features of other protocol layers, optimized to the characteristics of the lower layer and meet application requirements. This requires a structured, yet effective cross-layer information exchange as well as the exchange of control information among nodes.

3.2.1 Medium access control (MAC)

The MAC protocol schedules the transmission of frames over the wireless channel so that medium access is both fair and efficient. In the literature, a number of MAC protocols have been proposed [AM13]. However, none of them takes into account the novel concept of lossy communication, which requires that upon the reception of an erroneous frame the MAC protocol processes the received frame instead of discarding it. In the RESCUE system two networking topologies are considered: centralized (nodes connected to an access point or a base station) and distributed (typically an ad-hoc network). For centralized topologies, TDMA-based solutions will be the main area of study, because nodes are controlled by the central point. For distributed topologies, a decentralized MAC is needed, e.g., based on CSMA/CA. In both cases, traditional MAC protocols drop frames when a CRC error is detected. The MAC protocol in the RESCUE system should not drop frames with CRC errors, but transmit them towards the destination. It is assumed that the PHY and MAC headers should be received without any errors, which allows for recognizing the modulation type, source and destination addresses, frame length and other essential control information; otherwise the frame is discarded. This is a reasonable assumption, given that typically header information is transmitted with a more robust modulation scheme than the payload. Nodes that receive an erroneous frame should transmit their copy towards the destination. This means that several copies of the same frame can be transmitted over the network. In such a situation collision avoidance is even more critical than in typical networks. Additionally, in contrast to traditional MAC protocols, duplicate frames should not be removed by the RESCUE MAC protocol.

3.2.2 Automatic repeat request (ARQ) protocol

The ARQ protocol is responsible for the transmission quality of frames. Therefore, in the RESCUE system it is required to assure the communication quality between the source and destination nodes, while keeping the end-to-end distortion level lower than specified, even when using lossy links. The required

distortion level is specified by each user's quality-of-service requirement. Unfortunately, existing ARQ protocols – including their hybrid enhancements – are designed for point-to-point communication and do not consider the correlation between information sequences and retransmitted network-coded versions [NH14]. In the links-on-the-fly network each relay node performs decoding, interleaving, and encoding operations, which means that it possesses knowledge of the error rate. This knowledge can be utilized by the ARQ protocol in order to increase the efficiency of the ARQ mechanism. In particular, it is possible to perform retransmission not from the message source but from one or several relay nodes, even simultaneously by monitoring the distortion levels of the link-wise transmissions. It is also possible to perform retransmissions using a completely different route (or several routes). Therefore, the ARQ protocol in the RESCUE system will consider the specific number of routes used for a given retransmission. In case of unrecoverable errors at the destination node it can also drive the MAC and PHY layers at the source node to re-encode the same data in several copies using different codes. This data is again transmitted to the destination using multiple neighbouring nodes as forwarders and over multiple hops, which increases the probability of successful transmission over lossy links.

3.2.3 Multi-rate control

It is a common strategy in modern wireless systems to use a variety of modulation schemes and coding rates [KSN+08]. Adaptive modulation and coding allows for maximizing the throughput on links of different quality. In the case of multi-rate wireless networks, the knowledge of temporal characteristics of the channel becomes a key factor for the proper selection of the optimal data rate and assures the efficient transmission of frames in unpredictable and fast changing environments. In the RESCUE system the multi-rate algorithm shall receive detailed Tx/Rx statistics from the PHY and MAC layers. These statistics will be used to determine selected parameters and then utilized in the goal function to set the appropriate modulation scheme, coding rate, and Tx power for each neighbouring node. Choosing the optimal data rate at the MAC layer keeps the BER at a low level and, therefore, increases link utilization and network performance.

3.2.4 Routing

Traditional routing protocols rely on the fact that the packet to be forwarded has been correctly received on the previous link and the optimal next hop is selected among the candidates [HLT07]. Presuming that the lower PHY and MAC layers with their associated algorithms are able to support "links-on-the-fly", the RESCUE network layer needs to be capable of forwarding erroneously received packets and anticipating that the packet can be correctly decoded by the destination. For unicast communication, this implies that the forwarder does not select a single node as next hop, but several ones if possible. In ad hoc networks with broadcast characteristics, contention-based forwarding (CBF) appears as a good strategy that matches the links-on-the-fly requirement. With CBF, the actual forwarder broadcasts a packet to all its neighbouring nodes. Upon reception, the neighbours buffer the packet for a short duration of time and compete to become forwarder, typically using a timer-based mechanism. The contending nodes then overhear the other node's forwarded packets and may decide to re-broadcast the packet or to cancel their pending transmission.

Unlike in traditional wireless and mobile networks, with lossy distributed communication, multipath routing becomes a feature rather than an undesired side-effect. It is worth noting that existing routing protocols apply mechanisms to mitigate packet duplication, or even routing loops, as an effect of multi-path routing, such as packet sequence numbers, hop count/time to-live and exchange of control information. Utilizing the links-on-the-fly concept requires the re-design of existing routing protocols, or even a dedicated novel routing protocol.

3.2.5 Node coordination

As links-on-the-fly networks apply the redundant transmission of messages over different paths through the network, the load in the network increases and so-called "broadcast storms", well-known from multi-hop ad hoc networks, can occur. For this reason, resource allocation at one node influences the quality of other links and, thereby, achievable throughputs and fairness. Therefore, it is important to have knowledge of node behavior and the mutual coupling of nodes, which can be gained by observing the actual channel load and exchanging information between nodes. Both of these come at the cost of spectral and power resources for piloting and control. The environmental knowledge (e.g., channel information, knowledge of user/node locations, morphology) can be used to optimize network performance taking into account the costs and benefits of cooperation through information exchange of, e.g., environmental knowledge, scheduling decisions and probabilities, and cell loads/traffic demands.

Table 3.1: Summary of the functional requirements.

#	name	description	layer	scope
R1	Distributed encoding	Transmitters shall encode or re-encode a data packet with different interleaving patterns to form a network turbo code	PHY	source and relay nodes
R2	Multi-packet decoding	A receiver shall combine multiple differently encoded copies of a data packet	PHY	relay and destination nodes
R3	Re-encoding	A relay shall re-encode a data packet for re-transmission even if it has been erroneously decoded	PHY	relay nodes
R4	Scheduling	A transmitter shall schedule a data frame for transmission so as to minimize the collision probability	MAC	source and relay nodes
R5	Forwarding decision	A relay shall decide whether to forward a packet according to implemented policies	Network	relay nodes
R6	ARQ	The ARQ protocol shall ensure via re-transmission(s) that the destination is able to decode a data packet error-free or with a distortion level lower than specified	MAC	destination node, all nodes along the route
R7	Multi-rate transmission	Transmitter shall adapt the data rate to match channel conditions and/or QoS requirements	MAC	source node
R8	Routing	The routing protocol shall determine an advantageous route or multiple routes for data transmission from the source to destination	Network	all nodes
R9	Multicasting	A source transmitter shall transmit data intended for a group of terminal nodes of the network	Network	all nodes
R10	Broadcasting	A source transmitter shall transmit data intended for all terminal nodes of the network	Network	all nodes

4. Conclusion

This document described the most potential system scenarios, i.e., network layouts with communication applications, where the novel links-on-the-fly concept can be adopted and utilized. The first identified framework is *public safety operations* that take place in areas where the communication infrastructure, i.e., the cellular network is partially inoperable due to a disaster such as an earthquake. One distinctive difference between communication via the cellular network infrastructure and a fast emergency network roll-out is that, in the latter, the destinations may be multiple wireless hops away from the originating transmitters.

Furthermore, the nodes may be moving, which results in changing channel conditions and – in larger scale – in network topology changes. The RESCUE system aims at bringing connectivity to areas that would otherwise be unreachable. The traditional public safety applications to be supported are push-to-talk (PTT) and blue force tracking (BFT), but more advanced high-rate services such as video streaming are highly valuable for public safety operations as well.

The second potential framework for the links-on-the-fly concept is *vehicle-to-vehicle* (V2V) communication. Here, cars and other vehicles share, for example, safety-critical information about the road and traffic conditions with each other. The vehicles form a mesh network, where the node distances and the channel conditions may vary greatly as a result of constant node movements. Thus, the network is subject to frequent topology changes, and the main challenge is in the design of a routing protocol that is always able to react rapidly enough.

This document also listed requirements set on the RESCUE system design, in terms of both quality-of-service (QoS) and functionality. The QoS requirements in terms of throughput and latency were detailed, and it is recognized that the different communication applications that are to be supported by the RESCUE system, such as video streaming, text messaging, group communication (push-to-talk), and blue force tracking, have all somewhat different QoS requirements. Finally, functional requirements of the protocol design in the wireless mesh network were presented. The foreseen challenges for different protocol layers, from physical to network layer, were clarified and possible solutions discussed.

The RESCUE project will propose a number of innovative technologies for wireless multi-hop networking. These technologies can then be adopted into multiple existing and evolving communication standard, including, for example, the public safety extension of LTE and VANET technology based on the WLAN (IEEE 802.11/ITS G5) standard.

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Appendix A Simulation models

For simulation purposes a decent channel model must be found that fits to the described scenarios. On one hand, point-to-point wireless access technologies need to be simulated with this channel model. On the other hand, the links-on-the-fly concept and distributed coding algorithms rely on a varying network topology which must be also provided by the channel model. Therefore the channel model is split into two different layers of abstraction, the *link-level channel model* and the *fundamental network topology model.*

A.1 Link-level channel model

The *link-level channel model* describes the physical parameters of each wireless link between two nodes of the network. The wireless channel is modeled as a tapped delay line. The tap distribution, their gains and correlation are taken from the WINNER 2 [WIN2D112] channel models, which is a widely accepted model for wireless channels in urban and rural areas. Although WINNER 2 assumes a working infrastructure and communication is done between base stations (BS) and terminals, the model can be applied to the RESCUE scenarios when taking care of the plausibility of this assumption. Simulation results of the wireless access schemes based on these channel models will be provided in D1.3.

A.2 Fundamental network topology model

The *fundamental network topology model* describes the network as a whole from a higher layer of abstraction. The network is described as a collection of nodes where the quality of the link between each node is solely given by its capacity or, in case of multiple users accessing the link at the same time, its capacity region. Beneath the definition of each link capacity the model needs to describe the varying network topology. Therefore, a set of well understandable small-scale networks is defined. The model switches between the available topologies by the use of a Markov model that defines the probabilities to switch from one network topology to another. The set of investigated small-scale topologies and theoretical results on these will be given in D1.2. Simulation and theoretic results using the model for the fundamental network topology will be provided in the deliverables from WP2.

For modeling, the complex real-world network is decomposed into small network components, each being investigated separately. The characteristics of the links in the component networks that are modeled in the fundamental network topology model are 3-fold:

- Switching between lossless and lossy links,
- Switching between Line-of-sight (LOS) and non-LOS links, and
- The network topology and number of available routes.

Each change is modelled using a Markov model that describes the probabilities to switch from one state to another. The state transition probabilities have to be determined empirically so that they well describe the real physical propagation assumed in the RESCUE project

A.2.1 Switching between lossless and lossy links

The transition between lossy and lossless links is modeled by a change in the overall SNR of each link, i.e. changing the links capacity below or above the coding rate on this link. The appropriate Markov model is shown in Figure A.1. This Markov model is applied for every link in the component network.

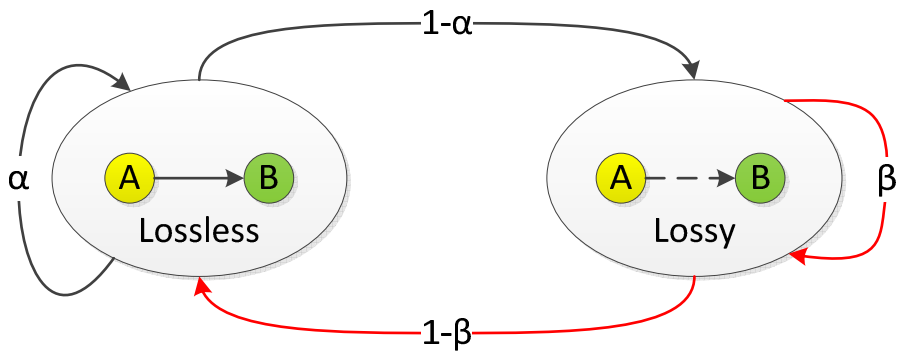

Figure A.1: Markov model for change between lossless and lossy link.

A.2.2 Switching between LOS and nLOS links

The transition for each link in the component network defining if it is a LOS or nLOS connection is also done with a Markov model. The appropriate state diagram is shown in Figure A.2. LOS links are simulated with a Rician distribution of the link gain whereas nLOS connections are simulated by zero-mean Rician, i.e. Rayleigh, fading distribution of the link gain.

For distributed coding and joint decoding there are cases when LOS connections are worse than nLOS. In these cases to achieve high overall capacities it is important to have multiple independent links in the network so that the destination can choose if it uses the LOS connections or only uses messages received via nLOS links.

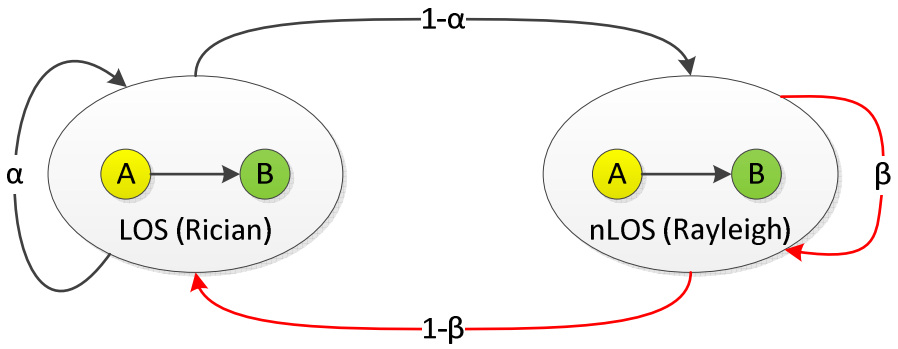

Figure A.2 Markov Model for transition between LOS and nLOS links.

A.2.3 Switching between network topologies

The network topology change is again modeled with a Markov model with an exemplifying state diagram shown in Figure A.3. The topologies that will be investigated are shown in Figure A.4. The Slepian-Wolf topology describes the scenario of Slepian-Wolf coding, when the link AB becomes lossy according to Figure A.1. However, the RESCUE system cannot rely on this particular configuration but it may also happen that AB and AC become lossy. Hence, these cases are considered in the fundamental network topology model. The CEO topology becomes the actual CEO scenario when AB and AD become lossy, but still, the system should also operating when e.g. AD and DC are lossy. Hence, the network model provides the means to simulate not only theoretic models but also more realistic scenarios.

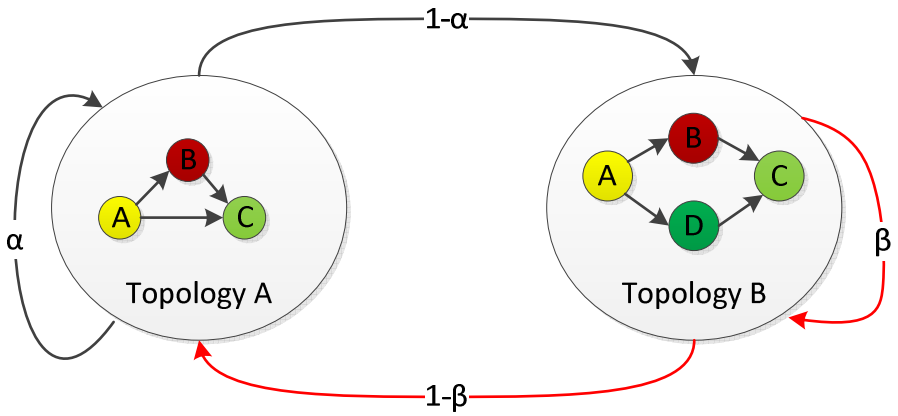

Figure A.3 Example Markov model for topology change.

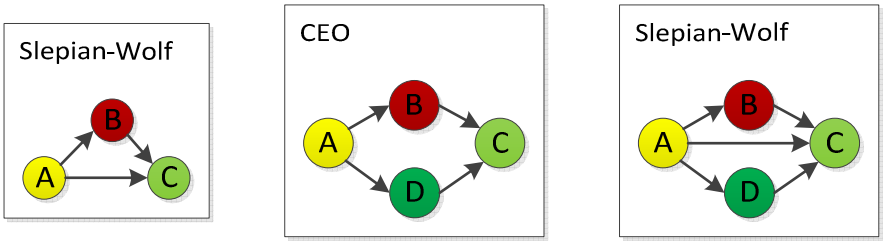

Figure A.4: Investigated network topologies.