3 TETRA Providing an Acceptable Security System Solution

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3.1 Introduction

Having examined the characteristics of the general class of PMR systems and the requirements for the design of autonomous systems with maximal security, we conclude that TETRA is a good candidate for satisfying in a technically sound way these requirements. Of course, certain improvements in standards and applications will have to take place as we propose in chapters 4-7. In order to prove our point, a comparison of TETRA with its closed competitors is in order.

This chapter, a substantial part of which is adapted from [1], the differences between TETRA and a GSM solution will be analysed in three dimensions in the hope to exhibit the clear and perhaps unique advantages of TETRA for security applications as will be shown in the subsequent chapters. The first dimension compares the applicable ETSI specifications and points out which functions are available according to the standard. Proprietary solutions will not be discussed on that level. The second dimension, a technical analysis, discusses how the end users and the operators perceive the differences between the network-solutions. Since it is possible technically to provide TETRA capabilities using GSM, an economic analysis focusing on the cost of the two alternative solutions, including capital and operational costs for the network infrastructure and end-user terminals which constitutes the third dimension, will be touched upon only briefly, because the applications of secure systems do not depend as much on economic terms but on their technical feasibility and the existence of international standards and on their ability to satisfy certain predefined requirements.

The methodical approach will be an analytic hierarchy process. Since there is a very strong correlation between the first and the second dimension, the results from the comparison of the air interface specifications will be used as an input for the technical analysis. Therefore, only the results from the technical and economic analysis will be used to derive final conclusions.

3.2 Hierarchical analysis

The picture below shows the structure of the hierarchical analysis.

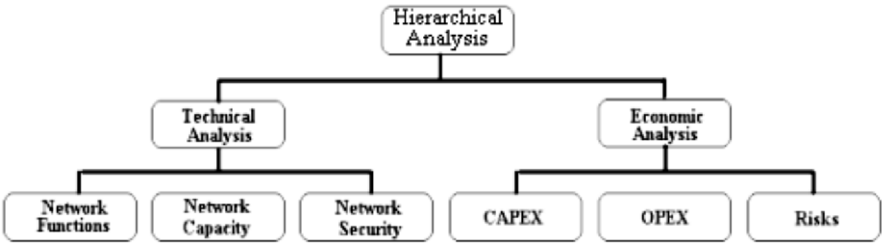

Fig. 1. Structure of analysis

Three different network solutions will be discussed:

- A new, independent TETRA network
- A GSM ASCI network which is based an existing GSM network
- A GSM ASCI overlay network which is based on an existing GSM network where only part of the cells are upgraded to support group call functionalities.

This approach assumes a certain cell overlapping in the GSM network and the comparison will be based on the following features and capabilities.

3.2.1 Air interface specifications

Group call functionality has an effect on nearly all elements in the network. For TETRA only the air interface is specified; the core network, including, for example, the signalling between base station and exchange, is manufacturer specific. In contrast, the GSM standard specifies also the interfaces between the network elements. The analysis focuses on the air interface specifications since they can be compared directly between the two standards. Impacts on the core network will be mentioned as far as they are relevant.

3.2.2 GSM ASCI

The ASCI (Advanced Speech Call Item) have been originally developed by ETSI and UIC (International Union of Railways). Therefore, the functional specifications are targeted firstly on railway communications. The ASCI features are part of GSM phase 2+ and consist of the following three items

- Voice Group Call Service (VGCS) — A teleservice
- Voice Broadcast Service (VBS) — A teleservice
- Enhanced multi-level precedence and pre-emption service (eMLPP)-A supplementary service

None of the ASCI features can be used with phase 1 or 2 mobiles. This means that dedicated terminals are required. Fallback and direct mode are both not defined in any GSM standard. An implementation would require proprietary solutions.

3.2.3 Enhanced Multi-Level Precedence and Pre-emption service (eMLPP)

The service consists of two parts — precedence and pre-emption. Precedence allows assigning priority levels to calls in combination with fast call set-up. If a higher priority call is set-up when all resources are in use, pre-emption allows seizing of lower priority resources.

There are 7 different priority levels. The two highest ones are reserved for network internal use (e.g. for specific broadcast calls) and are only available for calls within one MSC area. Additionally three different classes of set-up time performance levels are defined. For each user in the network, the maximum precedence level may be defined. If the user does not use eMLPP services, the network uses a default priority. Calls of highest priority and fast call set-up do require neither authentication nor encryption on the radio link. Authentication and encryption may be postponed or omitted.

The information about the different precedence levels is stored in the SIM of the mobiles and in the HLRNLR of the network. Implementation of the feature requires new features and parameters in MS, BTS, BSC and MSC. User data storage is needed in SIM and HLRNLR.

3.2.4 Voice Group Call Service (VGCS)

VGCS gives the possibility to establish group calls in a GSM cellular network [1]. A group call has basically three different kinds of participants: the talking subscriber, the listening subscribers and the dispatchers. Talking and listening subscribers can only participate in the group call, if they are within a predefined group area and if the group ID is stored to their SlM. Dispatchers can be located anywhere in the network and they are identified by MSISDN or ISDN. The maximum amount of dispatchers in a call is five. This restriction is caused by the definition of the conference call.

The service requires a new network element, the Group Call Register (GCR). It contains group details such as group area and dispatchers. The interface between MSC and GCR is not specified and therefore vendor specific. The group IDs are stored in the mobiles' SIM; updating of subscriber data over the air interface is not considered in the current specifications. This means that DGNA is not supported.

For the calling subscriber, a standard call set-up procedure, depending on the priority, is done. The BSC allocates resources and then invites the group members to the call using the new logical channel Notification Channel (NCH). The NCH sends the information for the whole duration of the call. This allows group members which are in the beginning of the call outside the group area, to join the call (late entry).

The network may pre-empt resources of lower priority. This is possible for emergency calls based on the specifications for eMLPP which are described above.

Only one mobile subscriber can talk at any moment, the other participants can listen to the common downlink channel, which means that if several subscribers are located in the same cell, they will listen to the same channel. By pressing the PTT, a listening subscriber can request a speech item. Speech-items are allocated on first come first serve basis without queuing. The talking subscriber always reserves a separate traffic channel on the uplink. The dispatchers can talk at all times and their speech is connected to the common downlink channel.

For the talking subscriber, standard handover procedures can be used within the group area. Listening subscribers have to initiate the handover themselves, since the system does not have any information about the users in the call. Seamless handover is not supported; idle mode cell reselection has to be used. A dispatcher uses standard handover procedures.

The described group functions are related to speech only. SMS to group numbers are not supported. A listening subscriber cannot receive any signalling while in the call, which means that e.g. sending and receiving of SMS during a call is not possible.

The calling subscriber or a dispatcher can terminate the call. Termination through inactivity after expiring of a timer is also possible.

For the calling subscriber, authentication and encryption are optional. They may be omitted or postponed when using fast call set-up. For listening subscribers, authentication is not possible but encryption is optional.

Like for eMLPP, modifications in all major network elements are required in order to support this feature. These are MS, BTS, BSC, MSC, VLR/HLR and SIM. Additionally the implementation of GCR is needed.

3.2.5 Voice Broadcast Service (VBS)

VBS consists of the same functionalities as VGCS with the difference that the speech is unidirectional. The calling subscriber may be a mobile user or a dispatcher. No uplink functionality is required for the listening subscribers. The network requirements are similar as for VGCS.

3.3 TETRA

The group call functionalities are defined in the ETSI specifications Terrestrial Trunked Radio (TETRA), Voice plus Data (V+D), Part 2: Air Interface (AI) [4]. These specifications also include the signalling for fallback and direct mode, however, they will not be discussed since a comparison to GSM is not possible.

Every TETRA subscriber, mobile or dispatcher, is identified by an ITSI (Individual TETRA Subscriber Identity). A group is identified by a GTSI (Group TETRA Subscriber Identity). The ITSI/GTSI consists of a country code, a network code and the subscriber identity. A mobile may be the member of different groups at the same time and it sends its membership-information to the Switching Infrastructure (SwMl) upon registration. The group information, like group area and members, is stored in the SwMl. The standard specifies updating of group information to the mobiles over the air interface (DGNA), for example, by authorized dispatchers.

When initiating a call, the subscriber sends the GTSI on the MCCH (Main Control Channel) to the SwMI. The SwMI allocates one traffic channel on every site within the group area and invites the mobiles to the call. Optionally it may reserve resources only on those sites, where members are located (shifting group call area). Priority queues are used to allocate resources. Pre-emptive services are also supported.

Group calls are always established as semi-duplex calls for all subscribers. By pressing the PTT, a listening subscriber can request a speech item. Speech-items are allocated using a priority queue. The talking subscriber uses the already allocated TCH (traffic channel) on the uplink.

In contrast to GSM, the mobile always initiates handovers in TETRA. The standard describes three different types of declared handovers. Seamless handover is supported for the talking subscriber. The listening subscriber can make an undeclared handover, which means that the mobile needs to move to the control channel of the new site from where it will be commanded to a traffic channel. If a subscriber moves to a cell within the group area where no TCH is active for the call, the SwMI has to allocate a TCH to the group call for that subscriber.

Since quasi transmission trunking is commonly implemented, the call will be terminated after expiring of a certain hang time. The standard also allows termination through the calling subscriber or a dispatcher.

Authentication is done during registration and roaming. The standard supports encryption with static or dynamic keys.

3.3.1 Comparison of specified features

Since TETRA has been especially developed for group calls, it fulfils most of the requirements. Some of the limitations in the table below are stated as “unlimited”. They reflect the standard, however effective limitations are, manufacturer specific.

Shifting group call area is basically possible for both technologies, TETRA and GSM ASCI. The air-interface specifications do not mention the implementation, since resource allocations are part of the core network functionalities. Several manufacturers have implemented the feature for TETRA; however, for GSM it does not exist. An implementation would require major modifications in the core network software, which is not feasible for economic reasons.[1]

Table 3.1. Summary of technical comparison

	TETRA	GSM / ASCI
Resource queuing priorities	Yes	Yes
Resource pre-emption	Yes	Yes
Speech item priorities	Yes	No
Speech item pre-emption	Yes	No
Late entry	Yes	Yes
Maximum group size	Unlimited	1024
Maximum amount of dispatchers in group	Unlimited	5

Maximum amount of sites in group call	Unlimited	Unlimited
Amount of groups per subscriber	Unlimited	50
Fixed group area	Yes	Yes
Shifting group area	Yes	No
Used traffic channels for a group call on N sites with X mobile dispatchers	N	N+X+1
Authentication of talking subscriber	Yes	Optional
Authentication of listening subscriber	Yes	No
Seamless handover for talking subscriber	Yes	Yes
Fast handover for listening subscriber	~1s	No

All above-mentioned features are input-information for the functional and operational comparison in the next chapter. Therefore, table 1 has not been taken into account in the hierarchical analysis process.

3.3.2 Technical analysis

The section below analyses, how the end-users and the network operators perceive the functionalities described in the previous section. It also discusses, which are the restrictions caused by certain solutions and how strong impact they have in practical situations. The section is divided into three parts: network functions, capacity and security.

Network functions

The network functions reflect which services are available for the end users including dispatchers and mobile users. Services, which have direct impact to capacity, will be discussed in a separate chapter. In contrast to commercial networks the functions also include network management tasks like the creating of groups. This so called tactical management allows dispatchers, for example, to create new groups for an upcoming mission (DGNA).

Group size

The TETRA specifications do not mention any group size restriction. Limitations are vendor specific. In case of Nokia SwMI, the amount of radio subscribers in a group is not limited and the maximum amount of dispatchers in a group call is 30.

GSM ASCI limits the amount of mobile subscribers in a group to 1024 and the amount of dispatchers to 5. The first limitation may be significant for broadcast group calls to large organisations. The second limitation is especially critical if different organisations are involved in a group call. Cross-organisational communication is important, for example, during a major incident; see also below (DGNA).

Dynamic Group Number Allocation (DGNA)

A dispatcher has to be able to allocate mobiles to temporary groups. This allows allocating resources for a mission, even if the mobile users belong to different organisations.

For GSM ASCI, there are different solutions to bypass the non-existence of DGNA:

- A set of pre-programmed groups could be used for special missions. However, this approach is hardly applicable for cross-organisational communication, since it highly compromises the numbering flexibility.
- A conference bridge could be used to combine groups of existing organisations [18]. This would reduce the amount of included dispatchers because of the limitation of S participants in a conference call.
- Proprietary solutions for over the air programming of the group data via SMS have been considered [1]. This seems to be the only acceptable solution for end-users.

The operators and end-user organisations should be aware of the fact that proprietary solutions often have negative influence on interoperability. Furthermore, the lack of competition typically causes higher equipment prices.

Short data messaging

The sending of short data messages to groups is a very effective way of informing the members of a group during an incident. This feature is supported by TETRA but not by GSM ASCI.

The sending of individual messages, as bypass, is significantly slower and causes additional load on the signalling channel. This increases the risk for control channel congestion during peak loads like emergency situations. Additionally, it is not possible to send individual SDS to mobiles which are engaged in a group call. This solution is not acceptable for the use in critical situations.

Call priorities

Queuing and pre-emptive priorities are specified for TETRA as well as for GSM ASCI. The Difference is that in GSM priorities are associated to subscribers. In TETRA different priorities can be given to subscribers or groups which lead to higher flexibility. Furthermore, TETRA supports more priority classes than GSM ASCI.

Main difference, however, is the lack of speech item priorities in GSM. In emergency situations it is important that a group leader can get a speech item and force the others to listen in order to achieve organised communication.

Priority scanning

No signalling for priority scanning is specified for GSM ASCI. If a member is engaged in a group call, she or he is not able to receive any other signalling. This restriction may be very critical for PSS users, where certain high priority group communications need to be available even if some of the members are engaged in another group call.

DMO and base station fallback

In case the mobiles are out of network coverage or the connection between exchange and base station is down, for example, due to a major accident, GSM based mobiles are not able to communicate. No base stations or mobiles supporting these functionalities are available on the market for the time being. The TETRA standard specifies both functionalities.

Network capacity

The required network capacity depends on different factors, like cell size, support of shifting area group call and the end-user requirement for call set-up times. The following subchapter discusses the impact of these factors on the amount of required traffic channels and bandwidth.

Cell sizes

Average TETRA cells are remarkably larger than GSM cells. Firstly, TETRA uses typically a frequency of 400MHz, while GSM uses 900 or 1800MHz. The propagation losses are theoretically proportional to the square of the frequency [12]. Secondly, commercial networks are typically capacity driven and PSS networks with less users are coverage driven. This means that the population density usually determines cell sizes in GSM.

The planned TETRA network in Germany consists of roughly 3000 cells. In contrast to that, the existing GSM network from Vodafone has 38100 cells using 15700 base stations. Assuming that most of the base stations have either 1 or 3 cells, we get 11200 three-cell base stations and 4500 one-cell base stations.

Overall we get an average relation of GSM:TETRA cells of 12.7:1. Due to the high capacity requirements in densely populated areas, the relation is somewhat higher in urban than in rural regions.

Taking into account the fact that there is a relatively high cell overlapping in the existing GSM networks, it would be basically possible to use only part of the cells for group calls. In urban areas, the network often consists of an overlay network providing coverage over a large area and micro cells improving location probability and providing capacity in densely populated areas. Building an overlay network by using only macro- cells for the group calls significantly reduces network costs because not all base stations need to be upgraded to support ASCI functionalities. Additionally we will see later that it reduces the generated load in the network. The main drawback, however, is a lower location probability which leads to a lower quality of service.

The table below shows the assumptions for the calculations in the next chapters. The average cell sizes for the GSM overlay solution are assumed to be double compared to the commercial GSM network.

Table 3.2. Cell sizes and bandwidths

	TETRA	GSM ASCI	GSM ASCI overlay
Average cell area (km^2)	120	10	20
Frequency re-use factor	19	12	12
Bandwidth per carrier (kHz)	25	200	200
Bandwidth per channel (kHz)	6.25	25	25

Traffic modelling of group calls

Models are commonly used to estimate the total traffic in a telecommunication system. In commercial networks the input data is subscriber density, area coverage and busy hour traffic per subscriber [1]. The call intervals as well as the call durations are assumed to be exponentially distributed (so-called Poisson traffic). In this case, the required amount of traffic channels can be determined by using the Erlang C-formula which is shown below.

Group calls used in PSS networks, however, have some special characteristics:

- The amount of users is known which means that the user density is derived from the total amount of subscribers and not vice versa as in commercial networks.
- In contrast to commercial networks, traffic is assumed to be constant over a longer period of time. The traffic growth is limited due to the constant amount of users. Network capacity seldom needs to be added. Network expansions are mainly for improving coverage.
- Semi-duplex group calls reserve one traffic channel one each site which is activated during the group call. Therefore, a traffic model for group calls typically includes the amount of cells activated in an average call. The assumption is that if a cell generates traffic to other cells due to group calls, it will also have to take traffic from other cells in the same proportion.
- The variance of the call intervals is higher and calls are of short duration since communication is used for tactical operation. During incidents, the capacity is significantly higher than during normal times, which leads to a bustier traffic distribution than Poisson traffic. ETSI recommends evenly distributed call durations and exponentially distributed call intervals for PSS traffic models [6]. In practice, however, Erlang C formula, assuming exponentially distributed call durations and intervals, is commonly used [1].

Erlang C formula:

The Erlang C formula assumes a queuing system and determines the probability that a call needs to wait longer than a certain queuing period. This probability is determined by using the two formulas which are described below. P describes the probability that a call is delayed (i.e. it needs to queue for resources):

$$P_O = \frac{A^X}{A^X + \left[N! \bullet \left(\frac{N-A}{N} \right) \bullet \sum_{X=0}^{N-1} \frac{A^X}{X!} \right]} \tag{3.1a}$$

N = Number of available communication channels

A = Traffic intensity in Erlangs (λ*H), where λ = call interval

H = Mean holding time (i.e. average call duration) in seconds

The value P_T describes the probability for exceeding a certain queuing time T. This probability is also called grade of service (GoS):

$$P(W > T) = P_T = P_0 \bullet e^{\left(\frac{(N-A)\bullet T}{H}\right)} \tag{3.1b}$$

W = Call waiting time in a FIFO queue.

T = A given queuing period in seconds

A typical value in PSS networks is a probability of 5% that the queuing time exceeds 5 seconds.

The described GoS is correct for a single site. In order to get the probability that all sites are included into a call after a certain waiting time, the value is depending on the amount of sites in the group call. Assuming that P_T is similar for all sites, we get the total PT according to the following formula:

$$\mathbf{P_{T(total)} = 1\text{-}(1\text{-}P_T)^n}$$

n = Amount of sites in the group call

Because group calls include different amount of sites, this effect is usually neglected in the calculations and only the site GoS is calculated.

Generated traffic:

Taking into consideration the assumption above, the generated traffic per cell is:

$$\mathbf{A = U \cdot \lambda \cdot H \cdot n} \tag{3.2}$$

U = Amount of users per site

λ = Busy hour call attempts per subscriber

H = Average call duration (λ · H = traffic per user)

n = Amount of cells included in a group call

In a similar way we can also define the traffic generated on a site by one single group:

$$\mathbf{A = \lambda \cdot H} \cdot G \tag{3.3}$$

G = Amount of active subscribers in the group

The amount of cells included in a group call is depending on the group size, the location and the moving behaviour of the group members as well as the average cell size. These parameters differ between the main user groups, police, fire brigades and ambulances. Below is a short description of their typical call behaviour.

Police

In normal situations, the average group size for traffic police is about 50 and the members are spread over the whole area or district. This group is used for informative purposes. During a mission, a group size is typically about 5 and the members are located in a certain, smaller area. The moving behaviour but also the size may be very different depending on the mission type.

Fire brigades & ambulance

During a mission, the group size is between 5 and 20 members which are located in a certain area. Members are typically moving only within small distances except when going to or leaving from places of interest.

The so-called user profile for traffic modelling uses a weighted average of the above described values between the user groups. The numbers below are based on traffic in existing TETRA networks [1].

The amount of active sites per call describes the amount of sites where at least one active subscriber is located. The numbers have been estimated using an even distribution of the subscribers in one forth of the group area, because in case of an incident, group members are typically located in a relatively small area.

Table 3.3. PSS user profile

	TETRA	GSM ASCI	GSM ASCI overlay
Mobile originated traffic (mErl)	7.3	7.3	7.3
Group size (users)	10	10	10
Group call area (cells for 400 km^2)	4	40	20
Active sites per call	2	6	5

Call set-up time and open channel

The call set-up time requirement for PSS users is 0.5s. Currently this is only achievable with TETRA and transmission trunking can be used for channel allocation. In GSM it would be basically possible to reduce the call set-up time to about one second, but this would require major changes in the core network software and topology. In practice this is for economic reasons not feasible in commercial networks. Therefore in GSM a traffic channel needs to be allocated for the whole duration of a communication (message trunking). If the call intervals are not predictable at all, a channel needs to be activated for a group all the time (open channel).

The amount of simultaneously active groups, which can be served per site, is significantly higher when using transmission trunking. The table below has been calculated using formulas (3.1) and (3.3) with a GoS of 5% for exceeding 5 seconds queuing time and an average call duration of 12 seconds. For example, a 2-carrier TETRA base station can serve about 8 times more groups than a single carrier GSM base station even though both have the same amount of traffic channels.

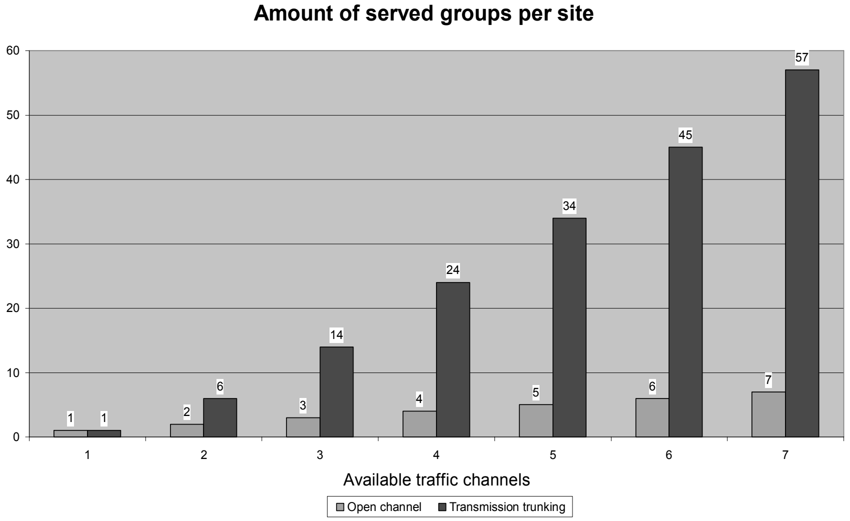

Fig. 2. Transmission trunking versus open channel operation

Shifting area group call

The support of shifting area group calls has a significant effect on the amount of traffic channels involved in a group call. Using the subscriber profile above, the amount of traffic channels which needs to be allocated for a group call, would be 2 for TETRA and 6 for GSM ASCI in case shifting group call area is supported. However, if this feature is not supported and high moving interest of the subscribers is assumed, all cells in the group area need to be activated. This would be 4 for TETRA and 40 for GSM. Taking into account that shifting area can only be realized for TETRA, the relation of channel occupations for a group call between TETRA and GSM is 1:20 in this example.

It may be possible [1] that a group call activate all cells where members are located plus the adjacent cells. It is obvious that this solution could only be used for user groups with low moving interest or if transmission trunking is supported. Otherwise, in case of message trunking, group members may lose the communication to the group when moving to other sites during the relatively long call duration. Additionally the small cell sizes in GSM increase the probability for cell changes during a call.

Required capacity on the radio network

Since the cell sizes are very different for TETRA and GSM it is not representative to observe the amount of used traffic channels. The required bandwidth or the amount of transceivers is more representative. The bandwidth can be either expressed in terms of radio channels or frequency.

The required bandwidth depends on the carrier capacity per site, the bandwidth per channel and the frequency re-use factor R. If the amount of cells in the network is smaller than the reuse-factor, then the amount of cells has to be used as R in the formula below. With a given carrier capacity C per site, the needed bandwidth in the network would be:

TETRA: $B = C \cdot 25\ \text{kHz} \cdot R$

GSM: $B = C \cdot 200\ \text{kHz} \cdot R$

We are considering two cases: a regional network with an area of 900 km and 400 users representing a medium size city with rural surroundings and a Germany-wide network with an area of 357 021 km^2 and 529 000 users. In both cases, the average group calf area is 400 km^2 and a group consists of 10 members. The assumption is that all users are active during busy hours. This might seem like an overestimation of the traffic, however, we will see that the calculated capacity for TETRA in table 5 is even slightly less than the recommendations for the Germany-wide network.

Since GSM does not support shifting area group calls, nor does it fulfil the required group call setup times, open channels have to be used for some groups. The following assumptions have been taken:

- One radio channel on each site belonging to the group call area will be activated during a group communication.
- 25% of the groups use an open channel for the communication, which means that a traffic channel is allocated all the time for the group.
- 75% of the groups use transmission trunking, which means that these groups have to accept longer call set-up times.
- The additional load generated by the talking subscriber and by mobile dispatchers has been neglected.

The channel holding time for quasi-transmission trunking has been neglected in both cases, GSM and TETRA. The generated traffic and required capacities per cell has been calculated using formulas 1 and 2 for groups using transmission trunking. The selected grade of service (G0S) corresponds to a probability of less than 5% that the channel queuing time would exceed 5s. In case of open channel, one Erlang is required on each site within the group call area during busy hours.

Since GSM ASCI is built on top of an existing network, the additionally required capacity has been determined. As reference, the Vodafone network has been taken, which consists of 38100 cells and 93600 transceivers [1] and has in average 18 traffic channels per cell. We assume that the capacity in the network is optimised on all sites, which means that 18 traffic channels carry up to 14.1 Erlang traffic during busy hours at the given GoS. This value has been added to the generated traffic through group communication and the sum has been used to determine the required amount of traffic channels. The traffic on the control channel has not been analysed and it has been assumed that no additional control channels are required for GSM ASCI. The average amount of carriers is a statistical value which therefore may be any decimal number. In case of TETRA, each site has one control channel for signalling purposes.

Table 3.4. Required radio network capacity for a small network[1]

Network size	900 km^2 and 400 users		
Technology	TETRA	GSM ASCI	GSM ASCI overlay
Amount of cells	8	90	45
Average amount of users per cell	50	4.4	8.9
Trunked traffic per cell	0.73	0.96	0.97
Open channel traffic per cell	0	4.44	4.44
Total traffic per cell in Erl	0.73	5.41	5.42
Required traffic channels per cell (GoS = 5% at 5s)	3	7	7
Required amount of carriers per cell in average	1	0.875	0.875
Required amount of transceivers in total	8	79	40
Required bandwidth in carriers	8	11	11
Required bandwidth in kHz	200	2200	2200

In this example, the required bandwidth for TETRA is 11 times less than for GSM. Interesting is that the traffic per cell and the bandwidth requirement are the same for both GSM solutions. However, the amount of transceivers in case of the overlay network solution is only half because of the double average cell size.

Table 3.5. Required radio network capacity for a large network [1]

Network size	357021 km^2 and 529000 users		
Technology	TETRA	GSM ASCI	GSM ASCI overlay
Amount of cells	2976	35703	17852

Average amount of users per cell	177.8	14.8	29.6
Trunked traffic per cell	2.60	3.24	3.24
Open channel traffic per cell	0	14.82	14.82
Total traffic per cell in Erl	2.60	18.06	18.06
Required traffic channels per cell (GoS = 5% at 5s)	6	19	19
Required amount of carriers per cell in average	1.75	2.375	2.375
Required amount of transceivers in total	5208	84795	42399
Required bandwidth in carriers	34	29	29
Required bandwidth in kHz	850	5800	5800

It is clear that the amount of sites is inverse proportional to the cell size. Together with the required bandwidth, this determines the total amount of transceivers in a network. Therefore, a TETRA solution requires significantly less carriers than GSM, even when regarding an overlay solution. The amount of transceivers does not only determine the size of the base stations, but also the amount of required transmission lines between base stations and exchanges or base station controllers. This value has therefore a major impact on the operational costs of the network.

The ratio of required bandwidths of GSM: TETRA is about 7:1 for the countrywide network. The reason that this ratio is smaller than for the regional network comes from the fact that GSM has a lower frequency reuse factor than TETRA and TETRA does not need to reuse frequencies in the small network. For the GSM solutions, the size of the chosen group call area and the user density are directly proportional to the required bandwidth. In case of TETRA, however, the size of the group call area has no influence to the capacity since shifting area can be used.

The graph below shows the required bandwidth in dependence of the average group call area. Input data are the same as for the calculation of the countrywide network above where 25% of the groups use open channel communication. For TETRA, the required bandwidth is constant at 850 kHz for a constant amount of users. If the group call area is 20 km^2 or less, the required bandwidth for GSM is 600 kHz. For larger areas, the required bandwidth grows more or less proportionally to the group call area and reaches significantly higher values than TETRA.

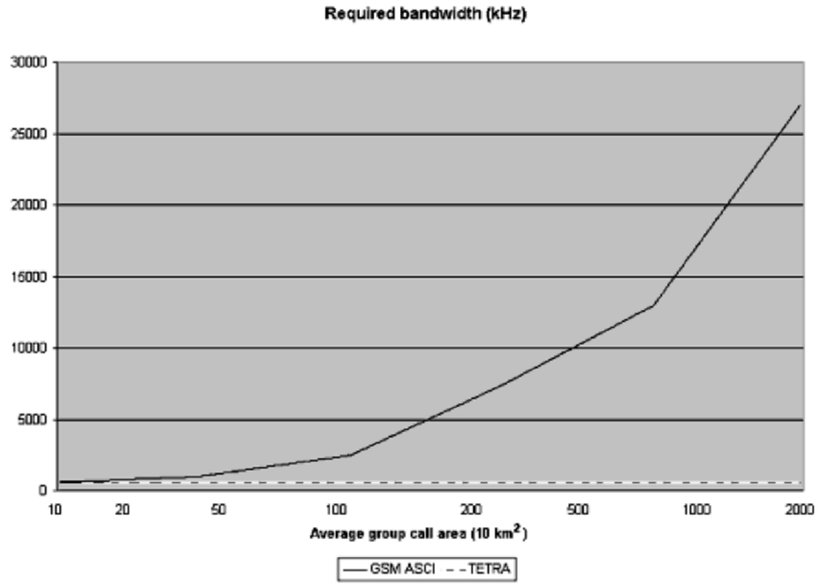

Fig. 3. Influence of group call area to bandwidth

As discussed earlier, the location of the groups is very seldom predictable and therefore, smaller group call areas can have a major impact on the quality of service perceived by the end users. For example, traffic police units move in very wide areas and a restriction of the group call area is in practical situations not acceptable. Therefore, a direct comparison between the two solutions is very difficult and one has to keep in mind that a network supporting shifting group call area always offers better quality of service since it is not realistic to use extremely large fixed group call areas. For further discussions, especially economic considerations, a group call area of 400 km^2 has been chosen.

It is obvious that keeping a channel open all the time wastes radio resources. The graph below shows, how the bandwidth requirement grows in the GSM network when groups are using open channel communication instead of transmission trunking. The calculations assume a group call area of 400 km^2. TETRA can offer fast call set-up times even if transmission trunking is used and therefore the bandwidth requirement is constant at 850 kHz. For GSM ASCI open channel communication has to be used for groups where fast call setups are required. The required bandwidth grows nearly linearly from 1.6 MHz if all groups use transmission trunking, to 18 MHz if all groups use open channels.

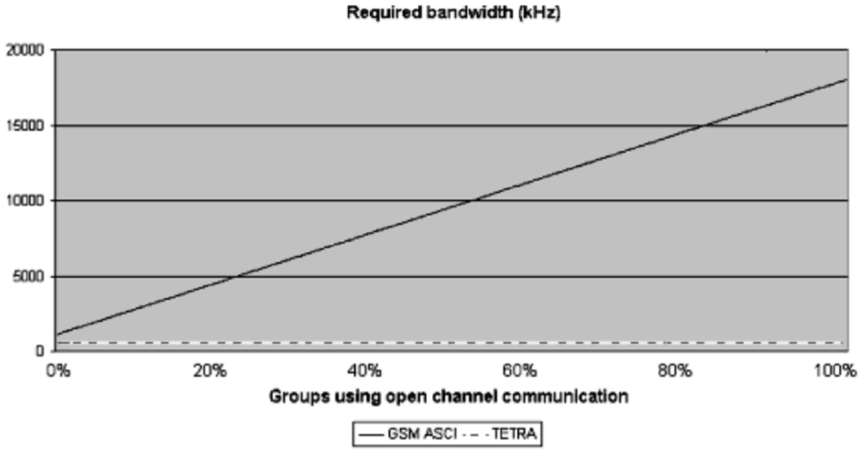

Fig. 4. Influence of open channel communication to bandwidth

For further discussions, it is assumed that 25% of the users require fast call set-ups and therefore use open channel communication in GSM.

Network security

Network security is mainly important for organisations where the communication is secret. The network should ensure that one not belonging to the group is unable to listen to the communication but also unable to disturb the communication. It should also be impossible to follow a certain subscriber by tracing or recording the signalling on the control channel.

Authentication

Authentication ensures that only mobiles with a valid key are able to use the network. In TETRA, authentication is done during the registration. The network rejects mobiles which return a wrong authentication key. In GSM, authentication is done during call set up and may be omitted during fast call set-up, Listening members in a group call are not authenticated in GSM ASCI since there is no uplink signalling during the call. This means that every mobile which has the group ID programmed to its SIM card, is able to listen to a group call. This is a high security threat for many PSS customers.

In TETRA networks it is possible that the mobile authenticates the network. This mutual authentication enables the mobile to detect fake base stations, thus it will not register to base stations not belonging to the network. Pseudo mutual authentication is also possible by using dynamic authentication keys. In such case it is not possible for a fake network to authenticate a subscriber, since a new key is used for each registration.

Air Interface Encryption (AIE)

AIE encrypts all signalling and call information on the radio path. Besides of the speech, it also encrypts the identities of the mobiles and the data messages on the control channel. This means that it is not possible to trace a mobile, for example, by following the signalling on the control channel. AIE is in use for both standards, GSM and TETRA. The TETRA algorithm uses longer keys and is supposed to be more secure than the one in GSM.

End-to-end encryption (e2ee)

E2ee encrypts speech and data between the end-points of the communication. Encryption and decryption are done in the end-terminals. The network infrastructure offers a transparent transport layer which is supported by both technologies. Dynamic keys may be delivered to the terminals using SDS/SMS. Even though, e2ee completely protects against eavesdropping, it cannot encrypt signalling information. E2ee encrypts all information on the traffic channel but not on the control channel. Therefore e2ee has to be used in combination with AIE.

Summary of comparison on technical level

The analysis has been split into three areas: network functionalities, capacity and security. Each of the areas will be summarized separately in order to keep high transparency. Since not all the features have the same importance, different weighting-factors have been used:

- Critical features: 2
- Default weight: 1
- Minor features: 0.5

The fulfilment of the requirements has been scored as follows:

- Completely fulfilled: 100%
- Minor functionality missing: 75%
- Major restrictions in functionality: 50%
- Only a bypass solution existing: 25%
- Feature not supported at all: 0%

Since the priorities of features are different for the various user groups, different weighting and scoring can be applied. The chosen values are interpretations from the related literature and practical experience. The different functionalities and features (arguments) have been summarised in tables which all have the following structure:

	Weight	Technology 1	Technology 2	Technology 3
Argument A	W_A	A_1	A_2	A_3
Argument B	W_B	B_1	B_2	B_3
Argument C	W_C	C_1	C_2	C_3
Argument D	W_D	D_1	D_2	D_3
Normalised sum of weighted grades	$Grade_1$	$Grade_2$	$Grade_3$	

The normalised sum of weighted grades ($Grade_1$) has been determined according to the following formula:[1]

$$Grade_1 = \frac{1}{\sum_{x=A}^{D} W_x} \cdot \left(\frac{W_A \cdot A_1}{\sum_{y=1}^{3} A_y} + \frac{W_B \cdot B_1}{\sum_{y=1}^{3} B_y} + \frac{W_C \cdot C_1}{\sum_{y=1}^{3} C_y} + \frac{W_D \cdot D_1}{\sum_{y=1}^{3} D_y} \right)$$

$Grade_2$ and $Grade_3$ are calculated in a similar way.

Regarding the group call functionalities of how they are perceived by end-user, GSM ASCI lacks of major functionalities which may be crucial for PSS users. Most of the missing features cannot be even compensated using proprietary features since they are directly related to the air interface signalling. For example, speech item priorities cannot be implemented unless specified by the standard.

Another major drawback of GSM ASCI is that no signalling is possible to listening members in a group call. The long GSM ASCl call set-up times cause that open channel communication has to be used for certain user groups. This means that mobiles are not able to receive any individual calls or SDS as long as the group radio channel is open.

Table 3.6. Network functions

	Weight	TETRA	GSM ASCI	GSM ASCI overlay
Group size limitations	1	100%	50%	50%

DGNA	1	100%	25%	25%
Group messaging (SDS)	0.5	100%	25%	25%
Call priorities	2	100%	75%	75%
Speech item priorities	2	100%	0%	0%
Priority scanning	1	100%	0%	0%
Late entry	1	100%	100%	100%
Fast handover	1	75%	50%	50%
Radio coverage	1	75%	75%	75%
Direct mode	1	100%	0%	0%
Base station fallback	1	100%	0%	0%
Normalised sum of weighted grades		0.675	0.168	0.158

The long call set-up times and the non-existence of shifting area group calls have major impact on the required air interface and core network capacity. Since GSM ASCI has been first of all developed for railways, shifting area has not been a crucial argument during the development of the standard. For PSS customers, where the location of the users is not known in advance and cell changes must be possible, shifting area is a critical requirement.

The row traffic channel usage takes into account that the speaking user as well as all mobile dispatchers require an own traffic channel in GSM.

Table 3.7. Network capacity

	Weight	TETRA	GSM ASCI	GSM ASCI overlay
Cell size	0.5	100%	50%	75%
Frequency reuse	1	50%	100%	100%
Bandwidth per channel	1	100%	50%	50%
Call set-up time	2	100%	25%	25%
Shifting group call area	2	100%	25%	25%
Traffic channel usage	0.5	100%	75%	75%
Normalised sum of weighted grades		0.541	0.225	0.233

Main drawback of GSM ASCI related to security is the fact that listening members in a group call are not authenticated and authentication may be skipped or postponed if fast call set-up is used. The importance of the security arguments differs much among the user groups. Rescue forces, like ambulance or fire brigades, typically do not need 100% protection against eavesdropping, however, for police forces proper authentication and encryption is a must.

Table 3.8. Network security

	Weight	TETRA	GSM ASCI	GSM ASCI overlay
Authentication	1	100%	50%	50%
AIE	2	100%	50%	50%
E2EE	0.5	100%	100%	100%
Normalised sum of weighted grades		0.476	0.262	0.262

In all three areas, GSM ASCI shows clearly lower performance than TETRA. The summary of the technical analysis is a weighted sum of the discussed areas. Network functions and security are weighted with 40% and network capacity with only 20% since its influence is mainly on economic level, where it will be considered once more.

Table 3.9. Summary of technical analysis

	Weight	TETRA	GSM ASCI	GSM ASCI overlay
Network functions	40%	0.675	0.168	0.158
Network capacity	20%	0.541	0.225	0.233
Network security	40%	0.476	0.262	0.262
Normalised sum of weighted grades		0.569	0.217	0.214

The graphical representation shows that the advantage of TETRA is similar in all three areas, which means that using different weighting has hardly any influence to the result of the technical analysis.

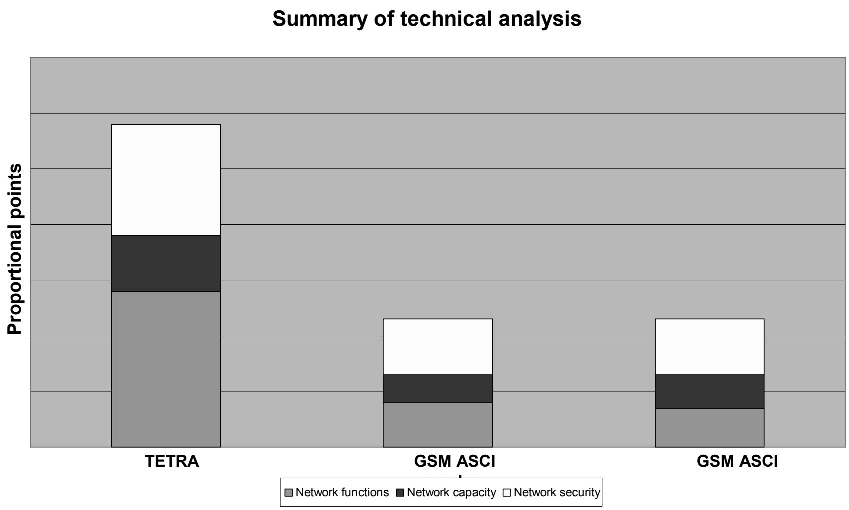

Fig. 5. Summary of technical analysis

A cost analysis based on the above technical comparison shows [1], that as far as which system provides a cost saving solution, by taking into consideration both Operating Expenses and Capital Expenses TETRA, provides a distinct advantage. This advantage is maintained even in the case when risk elements are included which make TETRA more vulnerable. As a matter of fact even combining economic results with technical for an overall comparison, TETRA wins by far.

Having these results as the basis of our optimism, in the following chapters, we present innovative and unique implementations of TETRA, in an effort to show that as TETRA improves, it can be used as the core of unified secure systems to handle WLANS, AD-HOC. An innovative improvement is proposed in the next chapter for the purpose of achieving an optimal channel assignment scheme.

References

1. Simon Riesen, The Usage of Mainstream Technologies for Public safety and Security Networks, Master's Thesis, 2003, Department of Electrical and Communications Engineering, Helsinki University of Technology