RAILWAY COMMUNICATION SYSTEMS

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Abstract

Communication Systems are essential for the safe and efficient operation of the London Underground (LU) railway, in all operating modes. This paper provides an introduction to Railway communications including the essential principles and applications used in the LU environment. Current technological developments and future strategies are discussed at the end of the paper.

1. Introduction

London Underground is the world's oldest metro system. The Metropolitan line opened in 1863. The LU network has 11 lines serving 270 stations. The bulk of the LU railway infrastructure was built in the latter half of the 19th and early part of the 20th century.

The LU railway comprises of 408 km of track of which 238 km is on the surface, 137 km is tube tunnel and 33 km in cut and cover tunnel. With an annual ridership exceeding 1 billion passenger journeys (equivalent to the entire UK national rail network) the LU network is the third busiest in Europe.

To support LU's vision of "a world class tube for a world class city", it needs to deliver a safe and reliable train service with high levels of customer satisfaction". The delivery of this objective has become difficult in recent decades due to LU's dilapidated infrastructure exacerbated by the lack of investment over many years. To resolve this, the UK government from 1998 to 2004 approved a number of long-term contracts to external consortia. Principally two types of contracts were used; PPP (Public Private Partnership) and the PFI (Private Finance Initiative).

Three PPP contracts (with capital spend predicted to exceed £30 billion over 30 years) were let for the maintenance and renewal of railway infrastructure including stations, trains, track and signalling. The private consortiums would borrow money from banks for the upgrades/ maintenance in return for periodic unitary payments /service charge from LU. The PFI contracts are also £1 billion+ specialised contracts for delivering specific services. These include **Connect** for providing integrated communications, **Powerlink** for providing electrical power for LU Infrastructure and **Prestige** covering LU ticketing services.

Unfortunately this outsourcing experience especially in the case of PPP has not been a positive one for TfL (Transport for London). Metronet InfraCo's BCV & SSL responsible for upgrading Bakerloo, Central, Victoria and all sub-surface lines respectively went into administration in 2007. Metronet was transferred to TfL in May 2008.

During scoping of PPP review period 2; Tube Lines, responsible for Jubilee, Northern and Piccadilly lines, claimed a substantial funding gap. TfL refused to cover this shortfall and instead bought back the equity from Tube Lines shareholders. TfL state this provides better long term value for TfL and its customers. Tube Lines transferred to TfL control in May 2010.

Of the three main PFI contracts; the Prestige contract with the TranSys consortium was terminated by TfL in August 2010 to save on costs. The Connect PFI and Powerlink PFI contracts continue to operate with the former expiring in 2019 and latter in 2028.

Numerous papers and reports (some commissioned by the UK Parliament) have been produced; looking at the underlying reasons why the PPP contracts failed. This discussion is beyond the scope of this paper. Interested readers are directed to references 1– 6.

Regardless of how engineering services are managed internally or externally via contracts, the delivery of LU's vision remains unchanged. Safety of the LU environment, service and engineering activities is regulated by the Office for Rail Regulation (ORR).

LU standards and industry good practice continue to be mandated for all renewals and maintenance ensuring safety and performance is not compromised. In this respect the balance between retaining and developing knowledge within LU against reliance upon external contractors becomes crucial. LU is the duty holder under ROGS 2006 and remains accountable for safety.

This paper provides an introduction to Railway communication systems. The context is the current LU operating environment and processes. The role of systems engineering and the asset whole-lifecycle is highlighted from the perspective of minimising safety risks and optimising whole-life cost. A look at the latest LU developments and improvements and potential future technological applications is provided at the end of the paper.

2. LU Communication Systems - Overview

Communication systems are deployed throughout the LU network to enable and support train, depot and station services. Support is provided locally and at line and network control centres. These systems not only facilitate normal, degraded and emergency mode of service operation but also provide some key interfaces/ functions to LU customers and emergency services during major incidents. Before describing the functions provided in these operating modes, it is necessary to understand the LU Communications asset taxonomy.

2.1 LU Communication System – Taxonomy

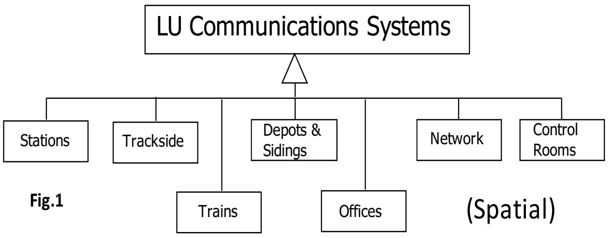


Fig.1

The UML class diagram shown in Fig.1 represents a spatial classification of Communication systems; ‘where’ the Communication functions are provided.

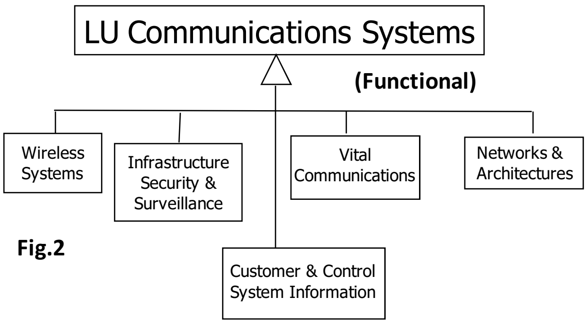


Fig.2

The diagram shown in Fig.2 is a functional grouping of LU Communication systems based on the proposed LU Communication Standards taxonomy. This can be extended to show details in each group as follows;

Wireless Systems

- Integrated (Connect PFI) network radio
- Microwave / radio leaky feeder CCTV for (OPO) one person operation train despatch.
- Radio Public Address microphone & interface
- Wireless Local area networks (LAN’s)
- Wireless surveillance CCTV

Infrastructure Security & Surveillance

- Intruder detection systems
- Infrastructure security Alarms
- Surveillance CCTV
- Access control systems

Vital Communications

- Tunnel Telephones
- Signal Post Telephones
- Emergency alarms & controls
- Voice alarms
- Integrated radio (Train)
- OPO CCTV

Customer and System control information

- Public Address systems
- Clocks
- Variable Electronic information displays (VEID)
- Passenger Help points
- Audio frequency induction loops (AFILS)
- Voice transfer units (VTU)
- Breakdown broadcast message system (BBMS)
- Traction earth detection
- Electronic Service Update Boards (ESUB)

Communication Networks and Architectures

- Local area networks (LAN)
- Wide area networks (WAN)
- Metropolitan area networks (MAN)
- Connect Transmission backbone
- Connect Integrated Radio network
- Auto Telephone network
- Station & Network management systems
- SCADA systems

The listed systems can be mapped to the spatial taxonomy (locations) shown Fig.1.

Stations

Surveillance CCTV (local)
OPO CCTV
Passenger Help Points
AFILS
Clocks
VTU’s
Connect Radio
Public Address (PA)
Voice alarm (sub-surface stations)
Variable Electronic Information Displays
Electronic Service Update Boards
Auto Telephone lines
Direct Telephones lines
Station management system
Audio & Video recording
Local area network
Tunnel Telephones (TT) (Sub-Surface &Tube stations)
Signal Post Telephones (SPT)*
Station Infrastructure Alarms
Access control system
Breakdown broadcast message system
*This asset is in the process of being decommissioned

Trackside

Connect Radio
SPT *
Tunnel Telephones (TT) (Sub-Surface &Tube stations)
Direct lines
Connect Transmission backbone
WAN/MAN's

Train

Connect Radio
SPT (Access to)
Tunnel Telephones (Tube sections)
Direct lines
Emergency alarm interface
In-Cab OPO CCTV & Saloon CCTV

Depots & Sidings

Connect Radio
SPT*
Tunnel Telephones
Surveillance CCTV
Depot Infrastructure security alarms
Depot Access control system
Depot Public Address
Telephone lines
BBMS
LAN (wired / wireless)

Offices

Auto Telephones
Access control systems
Intruder detection /BBMS
Public address (paging) systems

Network

Auto telephone network
Connect transmission backbone
Connect radio network
CCTV video network
Traction earth detection (telemetry lines)
BBMS

Control Rooms

Remote Public address (Line control rooms)
Remote CCTV viewing
Connect radio
Auto telephone lines
Direct telephone lines
BBMS
SPT*
Traction earth detection indications
Line /Network management system
LAN /WAN/MAN
Access control
Infrastructure alarms

2.2 LU Railway Operating Modes

The following account provides a description of the operating modes including how each is supported by LU communication systems.

Normal mode

In normal operation all communication systems are available for use, there are no major service affecting failures /incidents. Train services, stations and depots operate normally. Communication systems are used on a daily-basis to facilitate this 'normal' operation.

The station management system (SMS) where installed integrates many of the separate communication systems to form an integrated monitoring and control system. The SMS is used to safely and efficiently manage station operation. PA, VEIDS and ESUBS are used to provide information to customers relevant to their journey and safety. Connect radio is used by station staff to inter-communicate. CCTV is used to monitor crowding levels and incidents within the station areas. Help points are provided to enable customers to contact the station operations room in emergencies or for routine information.

LU line control rooms also are equipped with the Connect Integrated Radio. This is used primarily for regulating the train service. Connect radio enables communication with individual trains or to any user assigned to the relevant 'talk-group'. Other functions available include telephone lines (automatic & direct), remote CCTV (line-based) and remote operation of the Public Address at stations assigned to the line. Status indications are provided for Tunnel Telephones system and Traction earth detection system. The LU Network control has similar facilities. It is routine to record all audio lines in/out of a line control room and emergency video and audio in a station control room.

Degraded mode

Service affecting failures for example signalling, track-related, train or other incidents on the LU network may prevent the operation of a normal service. LU service operations managers with advice from senior engineers will decide if a reduced level of service can be offered. Operating a reduced (degraded) service often requires engineering and operational restrictions or mitigations, Railway Safety Principles and Guidance (RSPG) [7].

Degraded operation is usually a temporary arrangement permitted whilst system failures are being repaired or incidents are being managed to safety. Degraded operation should not be any longer than necessary as experience has shown that safety risks are increased during this state [8]. Communication systems are used to bring about service recovery as quickly as possible. Communication system design principles (see section 2.4) should ensure that systems are fault tolerant.

Abnormal mode

This is defined in RSPG as system operation under extreme load conditions. For the purpose of this paper this is considered to be deliverable by the full operating range of a given system. System designers are expected to factor in abnormal operation i.e. worst-case scenarios (include system failures) which may overload or stress the system to its limits. It is important that LU Operators/ and engineers are appropriately trained to recognise system conditions / behaviours and should be aware when mitigations / interventions are needed to ensure system safety.

Emergency Mode

In this mode customers and LU Infrastructure need to be protected from safety risks and damage respectively. Customer evacuation from the area where the hazard/ danger exists is the normal method to achieve this (customer safety).

Inter-staff and train to control room communication via Connect radio is the primary means for coordinating evacuations and detrainments. Connect infrastructure is also used by the 'Blue' light services during emergency incidents when their help is requested by LU.

For train detrainments in tunnel sections the train operator has the tunnel telephone system as a fallback in case the Connect radio fails. TT operation will discharge traction current enabling customers to be detrained and 'walked' safely to the nearest station.

Threat to human life can conceivably come from any of the top event risks in the LU QRA (Quantitative Risk Assessment); Fire, (Station / tunnel), derailment train collision etc. This threat is considerably reduced through the appropriate use communication systems.

These enable;

1. Immediate / early information from of the scene of the emergency to prime the rescue / repair teams.

2. Continual information updates from the scene of the emergency and inter-communication between LU staff and emergency services.

CCTV is often used by LU operational staff to coordinate station evacuations. In sub-surface stations the Public address –Voice alarm system linked to the fire panel can be used to automatically evacuate customers from the station.

Communication systems that are required to work during degraded and emergency operating modes must have a higher dependability and safety integrity than the service delivery systems that have failed thus causing the emergency / increased risk. This is discussed further in section 2.4.

2.3 Communication – Service & Support functions

Several service and support functions have been stated in the previous section and relate to the delivery of LU's vision and objective "to provide a safe, reliable and punctual train service." Essential functional requirements and supporting communication functions (based on section 2.1) are summarised in the table A below.

Table A

Functional Requirement	Communication System Support
Line & Network Control Rooms / Trains	
Audio – Train to Line Control Room	Connect Radio (Primary) Tunnel Telephones (Back Up) (Sub-Surface/Tube Tunnels only)
Audio – Line Control room to Train / or any Connect handset	Connect Radio
Remote CCTV viewing from Control room	Control room CCTV interface + CCTV video network
Remote PA Operation	PA System (Remotely Controlled)
Integrated Line Management	Line management system
Service information updates	Electronic service updates via LU Intranet (LU IM application) BBMS (alternative)
Audio recording incoming / outgoing lines	Digital Audio recorder
Video recording of viewed images	Digital Video- recording system
Audio communication (fixed line)	Auto telephone network (primary) Direct lines / BT line(s) (backup)
Emergency traction discharge from a current rail section (from line control room)	Tunnel Telephones (primary) for tunnel sections. Telephone line auto/direct. Shift Supply Engineer (Secondary)
Emergency traction discharge from a current rail section (from train / station headwall)	Tunnel Telephones (primary) Connect Radio (alternative – non immediate)
Train position information	*TrackerNet (LU IM application)
Control Room Clock	Clock synched to UTC
Network Control room - Similar to Line Control room	Connect Radio; Telephone lines; Remote CCTV; TrackerNet BT Lines
Station Environment	
Station audio - Inter- staff or to other Connect handsets	Connect Radio
Station audio – fixed line	Auto telephone network (primary) Direct telephone lines (secondary) BT line(s) (Backup)
Station audio – Customer to Station control room	Passenger Help Points; Lift PHP
Audio recording – emergency circuits (Lifts/PHP's etc.)	Digital Audio recorder
Local CCTV views	Station CCTV
Local PA operation	Station PA / VA system
Integrated station management	Station management system
Video recording of viewed images	Digital Video- recording system Time-lapse & full frame rate
Service information updates	Electronic service updates via LU Intranet (LU IM application) BBMS (alternative)
Customer Information	VEIDS / ESUBS Train information display
Station Security	Station Alarms / Access Control
Depot Environment	
Depot communication facilities similar to station	Connect radio/ CCTV/ PA system Telephone lines/ Access Control/ Intruder detection / Infrastructure security alarms

2.4 Whole-life design and Asset management – Discussion of System issues.

As stated in the introduction of this paper prior to engagement of PFI/PPP contractors much of LU infrastructure (including LU communication systems) was in a dilapidated state.

The Connect PFI approved in November 1999 has delivered an integrated (network) radio system, a transmission fibre-optic network using SDH technology (Synchronous Digital Hierarchy) and an ATM (Asynchronous Transfer Mode) video network.

This still leaves the other communication systems (listed in 2.1) provided in Stations, depot and trackside environments. Whilst a significant proportion of assets were replaced during the relatively short period of the PPP contracts, there still incomplete work targeted especially from the former Metronet programme.

Significant asset upgrades (including communications) and then the subsequent management of these assets; in an environment such as LU continue to be a major challenge for project teams. There are a number of causal factors for this problem, some typical ones include;

1. Inadequate (internal) knowledge and experience
2. Organisational issues
3. Poor decision support
4. Poor application of Systems Engineering
5. System design not based on whole-lifecycle

Inadequate knowledge and experience – the minimum expertise is to be able to validate and verify specified requirements. Communication systems can have a high level of internal and interface complexity. Therefore it becomes crucial that between the systems delivery and acceptance teams; sufficient expertise is retained to validate contractor designs and ultimately verify that the contractor has delivered “what was specified”.

Handed-over systems will become the responsibility of the maintenance and asset management organisations to ensure their respective strategies maintain but not reduce asset life and performance.

Minimum expertise for the maintainer is to understand ‘how’ to maintain systems to LU / manufacturer’s specifications. For the asset management team, it is to determine from maintainer reports /data) when to intervene to maximise asset life.

Organisational issues – resources need to be organised and optimised to provide coverage not only for project delivery but also for resolving core engineering and safety issues. Not having the appropriate resources at key stages of the asset lifecycle because of poor planning can cause delays potentially leading to losses.

A formal accreditation process is a useful tool that can help in role deployment and organisation of people resources throughout the asset lifecycle. The process can be used by project and maintenance managers to target specifically qualified and experienced people to specific tasks. The RACI matrix can be used to assign defined roles to specific stages / activities of a project (or other lifecycle phase) as shown below in table B. This methodology is used by LU in its PMF (Project management Framework) process.

Activity / Role					
	R	A	C	C	R
	C	R	R	A	I
	A	I	C	I	I
	C	A	I	C	C
	A	C	I	I	C

R = Responsibility ; A = Accountability ; C= Consult; I = Inform Table B

Knowledge and experience gaps need to be filled via targeted training and personal development plans. This is required to ensure the delivery organisation accountable for managing risks (business and safety); (London Underground in this case) can undertake the minimum validation and verification of specified requirements and delivered systems respectively.

Poor decision support – key decisions during project, maintenance or asset management have to be supported by competent resources, effective processes and timely information to minimise the opportunity for loss.

Poor application of Systems engineering - Station communication systems are usually delivered as part of a complex (station) upgrades programme involving multiple stakeholders and suppliers. Implementation involves many interactions (process, inputs/outputs) and may take several years to deliver.

In these situations systems engineering methods are essential to manage the complexity issues and provide greater confidence of project outcomes. LU has adopted structured delivery processes such as its PMF or the similar ‘V’ cycle to deliver its projects.

Both methods are requirements driven and incremental with discrete stages. Each stage has defined inputs and outputs. To reduce project risks key stages have associated approval gates with defined pass criteria that have to be met by the project in order to proceed.

For the systems engineering process to be effective it has to be coordinated across multiple departments and organisations. This coordination and cooperation needs to be maintained throughout the system lifecycle.

System design not based on whole-life cycle- successful system implementation depends on taking a whole-lifecycle approach to design, maintenance and asset management. This requires system designers to takes into account;

1. Operating requirements
2. Operating environment
3. System requirements
4. Whole-life asset management
5. RAMS / Dependability

2.4.1 Operating Requirements

For assured operation in normal, degraded and emergency modes of operation the design management authority (LU) will direct the contractor(s) to the performance and safety requirements via the system specification.

System designers need to take into account the range of variables and conditions that are required by the communication system to produce the functional outputs derived from the URS (user requirements specification). These variables will include known inputs and other assumed conditions needed for the system to work in each of the operating modes.

The inputs can be physical (signal or human action) or non-physical (software trigger/ input). The inputs can be intended or unintended either way they have to be considered with relevant conditions for their effect on system performance and safety in each of the operating modes.

This assessment requires designers to understand the range of inputs and conditions that can exist in the system operating environment. Using this knowledge the design can be tested against key functional and system requirements.

2.4.2 Operating Environment

The LU Railway is a harsh environment presenting the following factors to operating equipment;

i) extreme temperatures,
ii) water and dust ingress
iii) humidity
iv) mechanical vibration
v) EM interference
vi) Chemical & Electrolytic corrosion

LU communications systems need to correctly operate within their physical operating environments to agreed specifications, taking into account any of the above listed factors that may be present. They should not detrimentally affect other systems that physically share the same environment. Conversely the operational environment should not adversely impact the operation of the communication system.

The Communication equipment room environment and accessibility (for maintenance engineers) needs to be considered when testing for compatibility between the telecommunication system and its environment.

Additionally and importantly for systems designed to be fitted with HCI's, user involvement and consultation with human factors specialists is essential to ensure compatibility between the HCI's, equipment layout and the users.

To ensure integration with other systems the system integrator should mandate where possible the use of international or at least industry established standards (for hardware / software) and processes across sub-system supply chain.

In conjunction with the use of common standards and processes designers should seek consultation with human factors (HF) experts and actively involve the users during the development of the system.

Assessment of HF compatibility (especially) for HMI/ HCI's interfaces needs to allow for 5^{th} percentile adult females to 95^{th} percentile adult males. Computer modelling and or prototyping can be used to discover as many (operability) problems as possible during system development phases.

2.4.3 System Requirements

Defining system requirements is a complex task that cannot be carried out in isolation of the stakeholders. It is also true that input from the user groups alone cannot define the system requirements as "user requirements" is a subset of the total system lifecycle requirements.

In this context the system requirements include all functional and non-functional requirements including safety, performance, maintenance requirements and other project constraints.

To capture system requirements for the whole of the Communication asset life cycle a structured approach involving all the key stakeholders is required. The use of appropriate systems engineering (requirements/ visualisation /modelling) tools is recommended during the requirements elicitation / specification phase. These should provide backward/ forward traceability for each requirement throughout the project life cycle.

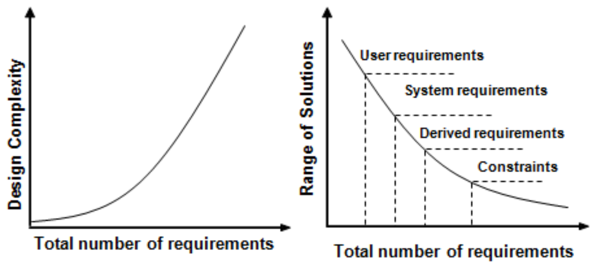
System design starts with the business /user requirements, these state 'what' the business/ user wants from the system. The total requirement set needed to design and implement the system is much larger than just these requirements.

The extra requirements come from the translation of the user /business requirements into a set of compatible functional and system requirements. This gives rise to further derived /sub-system design requirements.

When all the constraints due to interfaces, users and environment are applied the result is a large and complex requirement set.

The relationship between requirement count and design complexity and range of solutions is shown in Fig.3.

Fig. 3. Design Complexity, Solutions Vs No of Requirements



In any large requirement set dependencies between requirements is inevitable. These may give rise to potential conflicts which in the context of this paper may cause interoperability problems during service operations.

To minimise the occurrence of this problem designers should rigorously validate each requirement to reduce specification and consequent system complexity by ensuring that only necessary requirements are included.

It was discussed in section 2.2, that certain systems E.g. core communication and safety communication systems (as used in command and control centres) are required to continue working even under certain failure conditions i.e.in the degraded mode of operation.

This system characteristic is known as 'fault tolerance' and is achieved in Communication systems by using design strategies such as redundancy and diversity.

These techniques can be deployed in all aspects of the design and installation and at all levels, for example diverse routing of cables, data packets, redundancy in modular changeover systems and alternate switching paths in communications networks. These strategies can be applied to software design as well.

In safety-critical systems the failure of safety functions must be self-revealing; either by causing the system to failsafe or triggering an alarm to alert the users to prevent reuse until system is repaired. This latter requirement normally applies to fault-tolerant systems used in degraded mode.

Both emergency and fault tolerant communication systems are monitored for failures using closed loops (in wired systems) and watchdogs. Systems required to be fault-tolerant are normally designed to be protected against common-mode and single point failures.

2.4.4 Whole-life asset management

In the LU environment taking a whole-life view we recognise that for modern communication systems the product upgrade support for Communications systems when compared to other infrastructure assets is relatively short. Rolling stock and Signalling assets are expected to last and be supported for 40 years. In comparison the asset (operating) life requirements for PPP communication (upgrade) projects have ranged from 10 to 15 years.

Communications technology is an integration of many underpinning technologies, including analogue/ digital electronics, digital signal processing, embedded software systems. The world market for these rapidly advancing technologies is highly competitive.

There are positive benefits from this competition. Suppliers are motivated to improve product quality and offer a wider choice to their customer in terms of cost and functionality for a share of the market. It is not uncommon for manufacturers and suppliers to adopt planned obsolescence as a central policy for product development to maintain customer demand.

The general trend for the Communications technology as with many other systems built from mass produced parts has been to design and build where possible from COTS (Commercial Off The Shelf) based products.

Depending on the product and market competition; the original equipment manufacturer (OEM) may stop support for spares after a period of time having stopped production altogether or upgraded to a newer model. There is no guarantee that the upgrade is backward compatible and if offered for 'what duration'.

From LU's perspective another whole-lifecycle issue that needs to be considered when using COTS-based systems is that the specialist knowledge used to design and build the integrated system does not reside in LU.

When the system requires upgrading LU has to rely on the integrator who originally designed and or built the system. This could be a problem if the integrator is no longer trading and potentially costly if an upgrade is required due to obsolescence of a part of the system.

Communications systems designed and specified at the start of a major project, with a long Pre-implementation phase, may well be obsolete or nearing the end of their technology life cycle by the time the originally specified systems are finally implemented!

Thus it is advisable where possible to avoid stating design requirements around specific products. It is more prudent to specify functional and non-functional requirements at a level that is testable but not too detailed such as defined in a product specification.

2.4.5 RAMS

RAMS is an acronym that stands for Reliability, Availability, Maintainability and Safety. In the context of Railway applications there is a specific standard [BSEN 50126] that provide guidance. RAMS is a 'quality of service' measure that characterises a railway system's performance in normal, degraded and emergency mode of operation.

RAMS targets are initially specified at the start of the project as part of the tender specification. The supplier may revise these targets during contract negotiation. If the RAMS targets are contractual requirements then the supplier will provide a RAMS demonstration. This will include a period of time when reliability growth strategies are used to identify early / burn-in failures.

2.4.5.1 Reliability

Reliability is the probability that a given item will perform its intended function under given conditions for a specified time. For systems considered to fail randomly, reliability (R) is given by,

$$R(t) = e^{-\lambda t}$$

Where λ is known as the failure rate for specific item or system block and t is time period for which R (t) is required. Failure rate (λ) is specified as the number of failures per million hours for electrical/electronic elements. For systems whose elements have a constant failure rate, 1/λ = MTBF (Mean time between failure).

For Electrical/Electronic Systems the classical "Bathtub curve" is an approximation that is used to show the variation of failure rate during the system lifecycle. The Bathtub curve is a composite of three curves including "early failures", "useful life" and "wear-out failures".

The system maintainer and the user need to work together to ensure that the predicted useful life of the system is not prematurely curtailed thorough misuse, abuse or other external factors that can influence the operation of the system e.g. environmental factors, EMC factors. Good systems engineered designs should pick up these issues.

2.4.5.2 Availability

Availability (A) is the ratio of average time the system or sub-system is available and is given by:

$$A = \frac{Uptime}{Uptime + Downtime} = \frac{MTBF}{MTBF + MDT}$$

Where MDT = Mean down time. MDT commences upon the user reporting the system failure to the point when the system is reinstated for use.

Time to mobilise the repair team, fault diagnosis time and repair and hand-back time are included in the MDT. Modern Communication systems are modular with built-in computer accessible diagnostic facilities and test routines to reveal system faults and reduce the time for diagnosis.

2.4.5.3 Maintainability

Maintainability is the probability of a failed system /sub-system being restored to service within the prescribed times set in the maintenance agreement.
In BS 50126 it is defined as *'the probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources.'*

This metric incorporates the 'ease of maintenance' criteria including built-in test points/ indications and is linked to the competence and maintainer training.

2.4.5.4 Safety

Safety is a measure of a systems ability to remain safe. In BS 50126 it is defined as 'freedom of unacceptable risk of harm'.

MTBWSF (Mean time between wrong-side failure) when specified against a system measures how often that fails 'unsafe'. For safety critical systems this is expected to be > 10^9 hours. In EN 61508-1 tables 2 & 3 safety performance is measured using 'safety integrity levels' (SIL). This is an assigned level applicable to safety related systems.

This standard recognises five levels 0 (lowest) to 4. Level 0 represents non-safety. Safety integrity is the probability that a safety function will be performed successfully. This concept is further qualified by classifying a given safety-related system as 'low-demand or continuous demand'. The requirements for 'continuous demand' are more onerous.

In practice the term safety is more complex. Each wrong-side /unsafe failure will have consequence in terms of loss severity. London Underground's "Safety Certification and Authorisation Document" details the top risks and the mitigation measures used to reduce these risks to be ALARP (As low as reasonably practicable).

Safety is closely linked to availability. A practical balance needs to be realised in the design of a system that could become unsafe. This will be dependent on the probability of an unsafe state and the severity of this state. Over engineered designs will have more parts and therefore more chance of failure.

2.4.5.5 Software

Railway telecommunication systems containing micro-processors or other programmable devices will be dependent upon software to perform some or all of their required functions. The software (instructions) can be stored permanently in memory as 'firmware' providing read-only access.

Alternatively and more typically a system will utilise the 'firmware' to download much larger applications from magnetic/optical or solid state storage media. Either way the constraints to design, implementation, validation, and verification of software will depend upon the criticality of the functions that the software has to perform.

For software applications, guidance with respect to design, integrity, quality, validation, verification and is provided in various standards including:-

BS EN-50126: 1999
BS EN–50128: 2001
BS EN-50129: 2003
BS EN-50159: 2001 (Parts 1 – 2)
BS 61508: 2002 (Parts 1 – 7) (IEC – 61508)
BS 7925-1 & BS 7925-2
IEEE 829
IEEE 1012

Verification of software code on a line by line basis becomes very difficult and costly as the complexity of the program increases. The standards listed above look at the software development process, program structure, intrinsic - safety features etc.

In railway applications the concept 'safety integrity level' (SIL) is described in BS EN- 61508. See also 2.4.5.4.

2.4.5.6 Statutory Compliance / Industry Standards

Under the terms and definitions given in the ROGS (Railway Other Guided transport Systems) regulations 2006; all three roles; 1) Transport Undertaking 2) Infrastructure manager 3) and transport operator are applicable to London Underground. LU describes 'how' it complies with ROGS 2006 in its Safety and Certification document. This document focuses on LU's safety management system and how LU uses it to manage risks listed in its 'top event' register. Description of key safety and assurance roles with corresponding responsibilities and processes used is provided.

LU discipline and safety engineers adopt RSPG (railway safety principles and guidance) best known as the 'blue books', into system development, system installation, operation and maintenance. RSPG contain a total of 150 years accumulated knowledge of Her Majesty's Railway Inspectorate.

In addition there are the fundamentals and guidance for 'Engineering Safety Management – Fundamentals / Guidance' (known as the 'yellow books').

Compliance against more specific legislation such as the Disability Discrimination Act, (1995), Data Protection Act 1998 and EMC (Electromagnetic Compliance Regulations) 1992 are designed to address specific statutory requirements.

LU achieves compliance against these and other relevant legislation through its own internal standards and Industry standards and guidance where it is appropriate.

Industry good practice standards bodies relevant to Railway Communication systems include:

AES – Audio Engineering Society

BSI – British Standards Institute

CEN / CENELEC – Comité Européen de Normalisation

EBU – European Broadcasting Union

ETSI – European Telecommunications Standards Institute;

IEC – International Electrotechnical Commission

IEEE – Institute of Electrical & Electronic Engineers

ITU-T – International Telecommunications Institute (Telecoms)

ITU-R – International Telecommunications Institute (Radio)

ISO – International Standards Organisation

RGS – Railway Group Standards

RSPG – Railway Safety Principles and Guidance

The web sites for these standard bodies, is included at the end of this paper where further lists of standards and information may be obtained.

3. LU COMMUNICATION SYSTEMS

3.1 Communication Networks

Connect PFI Infrastructure

Connect Project - Background

Connect is a design, install, and maintain 20 year PFI contract awarded to Citylink consortium in November 1999. Citylink is a special purpose vehicle (SPV) specifically created for the Connect contract. Citylink shareholders and their percentage shares are as follows;

Thales group (33%)
Fluor (18%)
Motorola (10%)
Laing Investments (19.5%)
HSBC (19.5%)

Connect PFI predicted spend over 20 years is estimated to be around £1.5 billion. Connect assets revert to LU ownership at the end of the contract in 2019. An asset residual life of 4 years is required at contract end.

The Connect contract required Government approval hence tender evaluations had to be compared against a (PSC) public sector comparator. Invitation to tender documents did not specify any technology only output requirements.

Terrestrial Trunked Radio (TETRA) and SDH (Synchronous Digital Hierarchy) network was chosen by all bidders as best matching London Underground requirements.

Essential Connect objectives were,

i. Maintain all of the disparate legacy radio and transmission systems (including the long-line video transmission) up to the point when the new-build systems become available for use

ii. Maintain new-build radio new transmission net-work until the end of contract term (2019)

iii. Design and install a new integrated radio system to provide coverage of the LU network in accordance with areas defined in the contract

iv. Design and install an SDH (Synchronous Digital Hierarchy) transmission network comprising of;

   a) Voice & Data network

   b) Asynchronous Transfer Mode (ATM) based Video network

The Connect contract performance is measured using a service level agreement (SLA) defined in the contract. The Connect project started in 1999 when the WPE (ROTS) regulations 1994 were in force [13].

WPE Regulations required HMRI be notified of novel projects that could materially change operational or engineering safety / normal practices. The WPE notification was made in 1999/2000.

Design compliance was submitted to the HMRI in 2004 and Project completion was submitted in 2009 and approved by the ORR (Office of Rail Regulation). The London Fire and Emergency Planning Authority also accepted completion of Connect as part of the compliance against the Fennell recommendations originally published in 1989.

3.1.1 Legacy Networks

Prior to the Connect new-build Infrastructure being delivered there were several types of legacy networks being used.

i. Line-based train radio networks – these were used for providing communications between trains and Line service control rooms.

ii. Depot radio systems for serving train shunters, depot control rooms and trains in depots

iii. Station-based radio systems for serving station staff and emergency services each operating independently on different frequencies but on a common radio leaky feeder infrastructure

iv. E-Carrier Plesiochronous Digital Hierarchy (PDH) transmission network. The purpose of the PDH network was to interconnect the LU Auto exchanges and to transport inter-exchange traffic

v. Line-based switched CCTV video networks to relay CCTV pictures from station platforms to the British Transport Police and the Line service control centre.

The need for an integrated communications and radio in particular can be traced back to the Fennell report (1989) on the Kings Cross fire. Recommendations 111, 116 and 119 are commonly cited as requiring radio communications improvements. Fennell report [12]

3.1.2 Legacy Radio systems

Driver– Controller Communications & Train Radio

Early systems were not wireless. The first was called DRICO (Driver to Controller) based on the Tunnel Telephone (TT) system. A modified TT handset fitted with capacitors could be attached to the TT wires without activating the TT system (discharging traction current). A valve amplifier receiver in the traction feed substation would detect the Drico handset impedance and provide an audio path between the train and line controller.

The Victoria line completed circa 1968/69 used a carrier wave (CW) system. In this system a low frequency (RF) signal was injected into the traction rails from the train CW equipment. Trackside barrier units connected to the traction rails would pick-up this signal and relay this to a receiver unit in the signals relay room, for sending onwards to the line controller. The other way, audio from the Line controller would be received by a transmitter unit to be converted into RF for sending onwards to the train via the barrier unit.

First wireless systems were trialled in the mid seventies on the Bakerloo line. These were VHF PMR (Private Mobile Radio) systems; 165.xxxx MHz for train RX (receive) and 170.xxxx MHz for train TX (transmit). Leaky feeder cables installed on the side of the track /tunnel provided the RF coupling from and to the train. Line powered repeaters set at 20dB gain were fitted at 400m intervals to compensate for longitudinal loss in the leaky feeder cable.

Train radio for surface lines (Metropolitan and District) was installed between 1978 and 1986. VHF PMR was rolled out on the deep tube lines as well. To remove the requirement of a train guard a fail-safe OPO (T) alarm interface had to be installed. This TBC (Traction brake controller) alarm and was activated if the driver failed to push down on the TBC (also called dead man's handle) control for more than 30 seconds.

TBC alarm activation would cause the train cab radio to send out an alarm (Mayday) sequence to the line controller. This call would override other non-emergency calls on the incoming call stack. The line controller had to acknowledge the alarm and call the distressed train to reset the system.

The deep tube OPO (T) lines had the facility for the line controller to individually address the specific train during the alarm incident. When the Line controller addressed the train with the incapacitated driver he/she could speak with passengers over the train PA system as part of managing the emergency incident.

In total 4 frequency pairs were used across the whole of LU. Physical geographic separation and the use of channel change beacons enabled the 4 channels to be reused. Channel change beacons would be installed on the main depot (incoming and outgoing) roads.

In this way trains entering the depot would change to the depot frequency and those leaving the depot would revert to the main line.

Selective calling using a 5-tone CCIR sequence controlled transceiver squelch circuits and prevented third parties opening up a line radio channel. This did not prevent co-channel interference in some areas once the radio transceivers were opened during normal train radio operation.

In 1992 the Victoria line 'carrier wave' system was replaced with a new interim Motorola radio system. This used a continuous tone-coded squelch system (CTCSS). Also the Central line system was replaced as part of the line upgrade and re-signalling.

In 1998 an analogue trunk radio system based on MPT1327 was commenced which integrates Train and Station radio together for the Northern line. Also the Jubilee Line Train radio system was upgraded by the JLE project.

All of these separate radio systems procured and commissioned over many years were gradually migrated to Connect Integrated radio between 2006 and 2008 with the Northern line being last.

Legacy Station Radio

Station radio was provided in response to the **Fennell report** to facilitate Inter-communications between station staff and the station operations room or control point. These systems operated in the UHF band around 400 MHz and were provided at all deep level and sub-surface stations as well as certain key stations on the over-ground sections. Radio coverage was provided in all public and staff areas of the station as well as some disused areas which had to be regularly visited.

Separate (dedicated) radio systems were provided for the emergency services are also provided for the London Fire and Emergency Planning Authority (LFEPA) and British Transport Police (BTP). All three systems; Station staff, BTP and LFEPA used the same leaky feeder Infrastructure via RF combiner units

The LFEPA system was provided an alarm interface linked to the station operations room. The alarm interface monitored the integrity of the RF base station.

3.1.3 Legacy Video Transmission Network

This was an analogue FDM (frequency division multiplex) four channel system (7.5 – 30 MHz) based on the British Relay Mark 13 transmission system. The system was designed to transmit CCTV pictures to the Line Controller, Divisional Information Assistant (DIA) and BTP (British transport police). One channel was left spare.

The system was installed mainly at some tube and sub-surface stations, with CCTV views provided from platform headwall cameras. Not all stations were fitted with this capability. Later upgraded lines (Central, Jubilee etc) extended this facility to permit more views.

The station CCTV matrix could be addressed remotely by the line controller and his/her assistant and the (BTP). The video transmission was provided via co-axial cable fitted with a video repeater at each station. This system was life expired when it was replaced in 2008/9 by the Connect ATM video solution.

3.1.4 Legacy Transmission Networks

Early transmission networks were analogue trunk lines interconnecting the LU auto "Strowger exchanges" via the tandem exchange at Leicester square. A number of trunk routes were upgraded to G.703 E1 PCM routes. This required removal of loading coils from the trunk lines.

In 1985 LU Auto network changed over from Strowger to the MD110 based digital system. The LU digital MD110 auto exchanges are geographically distributed and were originally interconnected via an E-Carrier / PDH (Plesiochronous Digital Hierarchy) transmission network. Multi-mode fibre optic cables were used to create the PDH network.

The network topology consisted of two interconnected star networks. The central nodes provide the location of transit (TAX) exchanges. These provided switching of trunk (inter-exchange) traffic. The two transits were connected to each other via two E4 (fibre-optic) links and to the outer exchanges via E3 (34Mb/sec) fibre optic links. This configuration enabled the network to survive a failure of one TAX exchange.

By design inter-exchange auto traffic routing was split between the two TAX exchanges so that under normal circumstances approximately half the autos in a given location would be routed via a particular TAX and the remaining half diversely routed via the other TAX. Failure of the first choice TAX would cause calls to be automatically routed via the second choice TAX. The LUL digital transmission network was synchronised using a Master–slave hierarchy. One TAX was nominated network master (NM) and the other standby (SNM). All other exchanges including SNM would synchronise themselves as slaves to the NM.

3.1.5 The New Integrated Transmission Network

3.1.5.1 Core Network

The new transmission network is made up of a core SDH (fibre optic cable) network that supports;

1. Voice & Data Network
2. ATM Video Network

The core network is made up two interconnected STM-16 rings each with a capacity of 2.5Gbits/sec. The core network cable used is 48 fibre single mode. The SDH core ring network has 8 core nodes with connectivity to line rings as shown below in Fig.4.

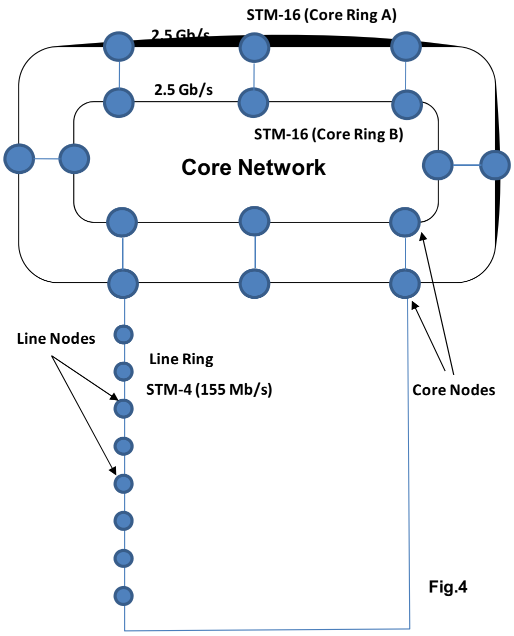


Fig.4

The design principles that have driven the network architecture include;

- Sizing
- Expandability
- Connectivity
- Flexibility
- Resilience
- Performance
- Demarcation
- Security
- Integration with other Infrastructure

Core network installation incorporates diverse cable routing strategies. Depending upon capacity / resilience requirements, cables can be installed in separate routes in different tunnel bores/sides of the track to any existing cable that forms part of the ring. Network timing is generated at two separate core nodes using GPS derived Primary Reference Clocks (PRC), with timing quality in accordance with ITU-T G.811. Other relevant ITU-T standards to the LU SDH network include the G.780 series, G.707 and G.803.

3.1.5.2 Voice & Data Network

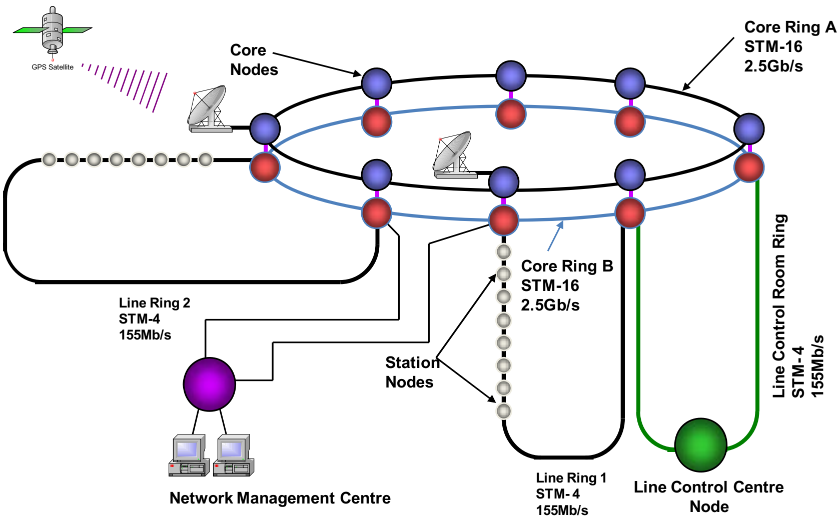


Fig.5

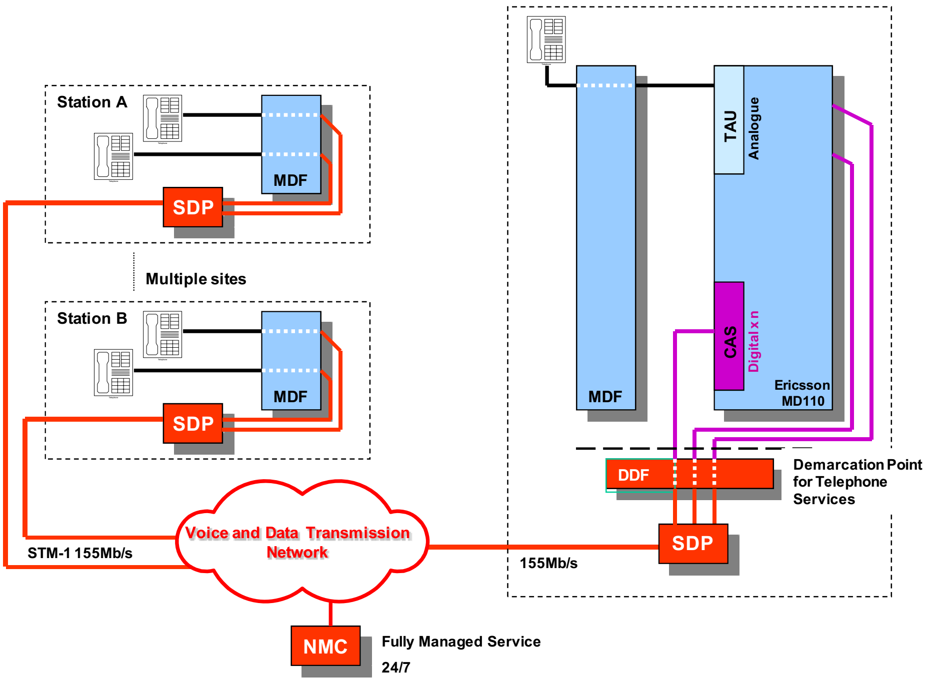


Fig.6

The voice and data network as shown Fig.5 provides transmission facilities for analogue and digital circuits, which together with an applied service level form the new system transmission services. The key network facilities provided by the voice and data network are:

- Circuit transport
- Circuit Cross Connection
- Circuit presentation and aggregation
- Circuit distribution

All circuits previously run over copper cables have within the scope of the Connect contract been migrated to the voice & data (transmission) network. These include auto phones, data circuits and telemetry.

The voice and data network has superseded the functionality provided by the former PDH network that interconnected the LU Auto exchanges. Transit (TAX) exchanges continue to switch trunk traffic but the routing of transmission data is now provided by the Voice and Data network.

The Connect transmission network is based on Marconi add-drop multiplexers; SMA-1 and SMA-16 for line and core rings respectively. Nokia Synfonet is used on the voice and data network as a cross-connect. SDH provides greater flexibility in multiplexing, demultiplexing, connectivity and higher channel capacity. As stated earlier The SDH network timing is generated by two physically separate and independent Primary Reference Clocks (PRC's).

Each PRC is synchronised to a Global Positioning Satellite (GPS) timing signal. This signal provides atomic clock accuracy. A free-running rubidium clock is available as backup if the GPS signal is lost. The Connect SDH is accessible via an SDP (Service Delivery Point). One or more SDP's are available at any given Service Delivery Area (SDA i.e. LU location). Larger stations (Multi-line) may have two.

Line control rooms and each LU MD110 telephone exchange has a dedicated SDP fitted with appropriate interfaces to support the different transmission signalling formats (CAS, (analogue circuits), DASS (digital external exchanges) DPNSS, (digital internal network), QSIG (Connect TETRA mobiles). This is shown in Fig.6.

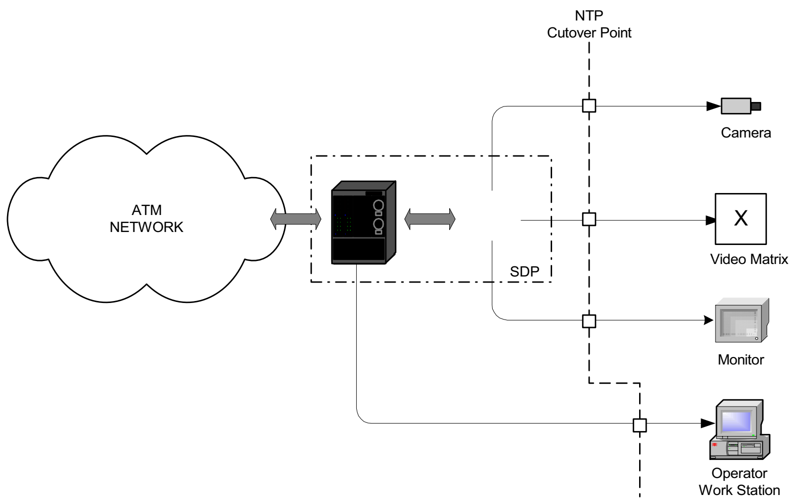


Fig.7

3.1.5.3 ATM Video Network

The Video network provides transmission facilities for analogue video circuits, which together with an applied service level will form the new video system services. The key network facilities provided include:

- Video circuit transport
- Video circuit routing
- Video circuit interfacing and control
- Video circuit presentation
- Circuit aggregation

The legacy video services have been transferred onto a new video transmission network, where appropriate. The new video network provides flexible network deployment and service delivery, and is resilient to network failure and provide remote operation and management.

The majority of legacy circuits were provided over a coaxial cable transmission system, with the additional use of some point to point fibre transmission links. The strategy for uplifting the performance of these circuits was to overlay a new video network and then to migrate the circuits onto the new network.

The new video network supports migration of future video circuits not currently services by Connect.
The Connect Video SDP (Service Delivery Point) provides the interface to the ATM video network.

The video SDP digitises the analogue CCTV video and connects to the ATM switches. The video information in the ATM frames is transported over the meshed ATM network (Part of the Core network) to the remote users (Line Control rooms, BTP and Network Control rooms).

3.1.6 The New Integrated Radio Network

The new Connect Integrated radio system is based on the ETSI standard 300-292. This is a digital trunked radio standard called TETRA. This acronym stands for Terrestrial Trunked Radio. The LU system is based around a Motorola product called Dimetra IP.

The Connect radio is based on a cellular architecture. It has 290 individual cell sites that are linked together via a switching system to provide radio coverage to LU users over the entire LU Network. Each cell site has its own multiple channel Base Station.

The Base Stations create individual cells of radio coverage that are centred predominately on LUL Stations and provide radio coverage to the approximate halfway point to the adjacent Stations (at which point the radio coverage from the adjacent Station takes over).

The New Radio System completed in December 2008 (Northern Line) and although implemented on a Line-by-Line basis; the system now operates as one integrated radio system covering the whole LU network.

Radio Equipment

The equipment that provides this functionality and makes up the New Radio System can be grouped into three primary categories:

- Fixed Infrastructure
- Propagation Infrastructure
- Subscriber equipment

3.1.6.1 Fixed Infrastructure

The Fixed Infrastructure is the brain of the system, containing the central processing that establishes calls and if required, transfers an ongoing call to the adjacent cell when the User is travelling outside the current cell's radio coverage.

The Propagation Infrastructure distributes the radio signals out of the Base Station to the whole of the LUL network; it also provides support to other radio users on the LU network. This includes connectivity with the emergency services 'Airwave' system. All of these services remain secure and independent of each other.

The subscriber Equipment includes the User based radio equipment such as mobiles (train mobiles and hand-portables) and fixed mobiles; which are desktop radios installed in stations and depots.

The fixed Infrastructure is a collection of standard products configured to provide the call processing, distribution and management of all aspects of the new Radio System. The Fixed Infrastructure broadly contains the following elements:

- Group Switch Controllers
- Base Stations
- Dispatcher Terminals
- Network Management Terminals
- Logging Recorder

The Group Switch Controller and Logging Recorders are centrally based elements.

The Base Stations, Dispatcher terminals and Network management terminals are distributed throughout the LU Network based on the operational requirements and are considered remote based elements of the fixed Infrastructure. Equipment cabinets /cubicles housing fixed infra-structure elements are ruggedized to a standard that is commensurate with surrounding environment.

Dispatcher terminals and the remaining Network Management terminals are installed in office type environments within Stations, Depots, and Line Control Centres.

Group Switch Controllers

The GSC controls the call processing, tracks the location of Mobiles, allocates channels, performs diagnostics and networks other elements of the Fixed Infrastructure into one cohesive system.

There are five GSCs inter-linked by high-availability fibre optic connections provided by the new transmission Network. Each GSC is centrally located in one of the five core CERs that contains both new radio system and transmission network equipment. Each GSC is connected to every other GSC and controls a number of Base Stations and dispatcher Terminals. This grouping is referred to as a 'radio zone'.

Base Stations

The Base Station transmits and receives the radio signals for its associated cell. There are 290 Base Stations in the New Radio System; a Base Station is assigned to each LU Station and major depots throughout the LU Network. Base Stations are located inside a CEC / CER depending on final site agreements. Each Base Station has a 4-hour battery backup in case of power failure and provides alarm and monitoring of amplifier failure, environmental conditions, power failure, and door position.

Dispatcher Terminals

The Dispatcher terminals provide remote and office based workers access to the new radio system. Dispatcher terminals provide its users with the same basic calling features available to the Mobile users along with a large number of additional features such as the ability to receive, process and clear emergency alarms, monitor multiple calls simultaneously, use enhanced call priority, and call interrupt functions.

Network Management Terminal

The Network management terminal provides system control, alarms and diagnostics to be performed on the system. This facility is available with the GSC, and control facility

Logging Recorder

Logging Recorders are provided at each core radio CER. Logging Recorders allow recording of all voice and data communications except calls made in Direct Mode Operation (Radio system functions used during an incident that caused a local system failure.

3.1.6.2 Propagation Infrastructure

Essentially, Propagation Infrastructure distributes the Base Station RF and delivers it through-out the LU Network; to deliver RF over the entire LU Network, a large quantity of RF Cable and related equipment is required.

To meet the diverse requirements of the entire LU Network it is necessary to develop solutions for specific / known requirements. To accommodate these solutions, the design of propagation infrastructure for the new radio system is grouped into three broad categories: Leaky Feeder, Distributed antenna systems, and re-use of existing leaky feeder.

3.1.6.3 Subscriber Equipment

Subscriber equipment gain access to the new radio System via RF. There are three elements of the New Radio System that fall into the grouping "Subscriber Equipment":

Train Mobiles
Hand-portables
Fixed Mobiles

These elements provide the user with similar functionality; which in its simplest form is push-to-talk and release-to-listen. All TETRA mobiles have via the LU Fleetmap access to defined 'Talk groups' (other users). These are selectable via the subscriber equipment. The Fleetmap database is configured /updated in software.

Train Mobiles

A train mobile is provided in each driving cab as per LU instructions. Train Mobiles are standard products with a custom Human-Machine-Interface and rugged housing that will provide additional vibration protection. The location of Train mobiles is tracked by the radio system to the precision of an individual cell. The train alarms provided include the TBC OPO (T) alarm and Mayday (high priority) alarm.

Fixed Mobiles

Fixed mobiles are standard mobile radios with an external power source and local speaker to allow for semi-permanent mounting at a desktop location. The Fixed mobile has the same functionality available to its users as those available to Mobile users. They are primarily for use in stations and depots where the full functionality of a Dispatcher Terminal is not justified.

Handportables

There are two types of hand-portables available, a standard version and an enhanced version. Both handportables have much of the same functionality. The enhanced handportable has a keypad for data entry such as to enter telephone numbers or to create user generated text messages.

Comparing TETRA and GSM-R

In the UK and the rest of Europe these are competing ETSI standards used in various environments. GSM-R was created specifically for railway environments and is used in the UK by the national railway network. TETRA used by LU is also used in many parts of the world particularly by emergency services and some railways. The following is brief comparison of the two.

TETRA & GSM-R Comparison	
Advantages	**Disadvantages**
TETRA - Higher levels of security performance. - Spectrum efficient - Low call set up time - High speed (mobile) working -flexible connectivity in routine and emergencies - works in fallback mode during system failures -less infrastructure needed for same coverage	Technology is expensive TDMA /Pulsed operation may cause interference Data transmission speed limited (slow)
GSM-R – Interoperable with public GSM network and ERMTS -designed specifically for railway safety / reliability Highly scalable	Call set up long compared to TETRA Low spectrum efficiency

3.1.2 Telephones

These are the mainstays of a railway communication network. Principally there are two types of systems in common use:-

- Direct Line telephones;
- Automatic telephones.

Direct lines

The use of direct lines pre-date automatic circuits. They provide point-to-point communication between two given nodes. Typical applications include secure voice communications independent of Automatic circuits and other communication systems such as radio which may have failed.

Hard-wired and relay-based LU direct line circuits are being steadily decommissioned and functionality being replaced by Connect radio, digital circuits or auto lines configured as non-dialled circuits (hot lines). Typically LU stations, Depots /sidings and control rooms are equipped with direct lines.

Automatic Telephones

Traditional automatic lines provide “any to any” phone connection via an Automatic telephone exchange which “automatically” connects the caller to the desired telephone. Automatic functions performed by the exchange manage calls from start to termination. During this process the exchange is performing tests on the called circuit whilst keeping the caller informed via distinct recognisable tones. Average connection time is typically achieved within 1 second of dialling.

The current Auto system was commissioned in 1985 from the life expired (electro-mechanical) ‘Strowger’ technology to the digital distributed stored program control (SPC) system, MD110. The MD110 digital exchange was based upon the then relatively new AXE architecture. The LU MD110 system was the first of its size and complexity to be commissioned in the UK and Europe. The AXE distributed architecture, (based on the APZ central processor) is widely deployed around the world. The extension types supported by the MD110 include:-

- Analogue – Normal features DTMF dialling;
- Digital - Feature rich (Business application);
- Emergency (Non-dialled Connection) Lift handset to make call to pre-defined destination;
- ISDN – High bandwidth link 2 x 64 Kb.

The AXE architecture is modular and highly resilient. Single failures in either hardware or software modules cannot cause the whole system to fail. The AXE architecture is flexible, easily re-configurable in both hardware and software. This feature provides for future proofing.

3.1.3 Vital Systems

Signal Post Telephones (SPT)

Signal Post telephones are safety circuits used for emergency communications by train operators when the connect radio system has failed. The SPT is essentially a direct line powered centrally from a telephone panel with either backed up 24V or 48V d.c. They are installed trackside normally on running signal posts. The high availability of Connect radio has led to a policy decision to remove SPT functionality except in locations where there is an interface with other train operators requiring SPT’s to communicate with LU in emergencies. Asset recovery is being programmed with maintenance activities and other project opportunities as they become available.

Tunnel Telephones

The Tunnel Telephone (TT) is an emergency traction current discharge system that allows train operators and station operations staff to detrain passengers safely in emergencies with traction current switched off. The need for Tunnel Telephones can be traced to HMRI RSPG part 2 section A and C. The system is installed in all tunnel sections exceeding one train’s length.

The system is classified as safety critical and therefore operates on failsafe principles. Secondary functions provide voice links to the Line Controller as a useful backup in case of radio failure. TT voice is recorded at the Line control room. Each LU railway line has its own tunnel telephone system. The TT system can be seen externally as two bare wires running parallel along the length of the tunnel. With the exception of the Victoria line, a platform interface in the form of a TT instrument is provided at each headwall. This enables traction current to be discharged from the station platform. LU Traction feeding is sectionalised to minimise power loss and prevent electrical earth faults from affecting large parts of the network. The TT sections are designed where possible to physically align with traction current sections.

The Tunnel Telephone design is essentially minimalist. The system is constructed from highly reliable components. The wiring configuration ensures high resistance and open circuit failures will cause the system to failsafe. The TT system design is a trade-off between maintaining an acceptable in-service safety and in-service availability. The former is assured by safety design whilst the latter by using highly reliable components and a minimum component count.

Once traction current is discharged it cannot be recharged until the TT is reset or over-ridden. This feature is exploited in the safe system of work known as ‘Enhanced Line Clear’. This is used in conjunction with site hand-back procedures to protect personnel working in tunnels after close of traffic.

Voice Recorders

Voice Recording systems form important part of post incident investigations and have been provided to comply with the recommendations of the Clapham Accident Report (1989- A Hidden) All emergency voice communications including key telephone and radio conversations, at Line/ Service Control Centres, Network operations Centres and station control rooms are recorded. Digital voice recorder systems have replaced the former reel-reel analogue recorders. These support the time and date stamp for evidential purposes and rapid replay of key messages pre and post-incident.

3.1.4 Infrastructure Security & Surveillance- CCTV

CCTV is primarily used on for surveillance in the LU environment. CCTV is also used as a safety function for crowd control and also to assist in the complete evacuation of stations (especially underground) in the event of a major incident or emergency. The security function to deter criminal behaviour including trespass, and dangerous behaviour is import-ant but secondary. The design strategy in stations is in most instances driven by LU operational requirements biased towards surveillance and not to security as may be the case for CCTV views on gate-lines or depots.

CCTV Operational requirements

There are four specific requirements;

Monitoring and Control – to enable an observer to determine the number and direction, speed of movement of people whose presence is already known.

Detection – following an alert, observer can ascertain after a search with a high degree of certainty whether an individual is visible in the images displayed.

Recognition – an observer can say with a high degree of certainty whether an individual displayed is the same as one seen before.

Identification – The picture quality and detail should be sufficient to enable the identity of a subject to be established beyond reasonable doubt.

CCTV Coverage

Typical areas to be covered by CCTV include:-

- Station - public areas;
- Subways, passageways;
- Security doors and access/egress points;
- Key security areas;
- Platforms;
- Trains – Saloon;
- Depots, perimeters and sidings;
- Car parks

When used in for surveillance the required operational requirement for the surveyed area must be delivered. This applies to security requirements for CCTV used for pinch points / building perimeters etc.

If images could be used for evidential quality for potential prosecution, it is essential that images are large enough, clear enough with unique image ID, date and time stamps in the video recordings.

Accessibility to video recordings without disrupting the recording process is essential. Coverage should be free from blind-spots. Field of view must not be obstructed.

The 'Secure Stations Scheme' sponsored by the British Transport Police and the UK Government has been instrumental in challenging the design of stations and associated infrastructure including enhanced station lighting and generally improved visibility.

UK CCTV systems need to comply with relevant legislation including the Data Protection Act 1998 together with associated Codes of Practice. CCTV system operation and management must be compatible with Freedom of information Act 2000, Human rights Act 1998.

QOS (Quality of Service) measurement

CCTV system image quality can be assessed using recommendation ITU–R BT.500–12 'Methodology for the subjective assessment of the quality of television pictures'. This method does not require any special equipment but assessors are required to be trained to detect image defects. Objective testing can be carried out using test target such as the 'Rotakin'. This was originally developed by Police Scientific Development Branch (PSDB). This target is a matt black board 1.6m high by 0.4m wide with a human head profile at either end. It has high contrast resolution bars and a wedge chart to enable image resolution and other parameters to be objectively captured and baseline recorded.

There are 12 bars provided on the Rotakin target marked A – M. These are designed to cover a resol-ution range from 500 to 20 TV lines (TVL). When the Rotakin vertically fills the viewing monitor an image height of 100%R is said to have been achieved. At this height each bar or minimum wedge width (as appropriate) corresponds to an image resolution defined as TV lines as shown in table below.

Rotakin Bar	TVL@ 100R	Rotakin Bar	TVL@ 100R
A	500	G	200
B	450	H	150
C	400	J	100
D	350	K	80
E	300	L	40
F	250	M	20

The CCTV cameras, infrastructure and associated system should be capable of producing an image to meet the operational requirements with the following R values:-

- Monitoring - not less than 5% x R
- Detection - not less than *10% x R
- Recognition - not less than 50% x R
- Identification - not less than 120% x R

*LU require 20%R for detection

Operational management

The display and observation of CCTV images should be accessible from control locations such as station supervisor office, line control centre, security office, depot control, train operator cab. Control rooms should be secure, and ergonomically designed to allow situations to be pro-actively monitored by trained CCTV operators. Selection and control of images should be subject to various levels of authorisation to ensure compliance with the Data Protection Act 1998.

Recording (analogue / digital)

Analogue CCTV systems that previously used SVHS recorder are being phased out with digital recorders as stations are being upgraded. The reason for this is that SVHS recorders and tapes are obsolete and no longer maintainable. The potential benefits of digital recording are numerous, including for example improved security, image quality, and system flexibility.

A number of problems and issues did arise on early installed systems. These were related to video image retrieval and playback. This is particularly important if the video evidence is to be admissible in a court of law to acquire successful prosecutions.

Various guidance documents produced by the HOSDB (Home Office Scientific Development Branch) provide a useful base-line for mass CCTV users such as LU and its suppliers.

The main problems found with early digital recording systems were:-

- Export of video data - Export format varies with manufacturer and is unnecessarily complicated;

- Playback of video data – Often specialist (proprietary) playback software required to view exported data;

- Storage of video data – Despite advances in storage technology, (Hard disks, CD-R, DVD-R etc.) The large number of camera's at LU stations and the requirement to store images for 14 days, at an acceptable level of image quality is a storage and retrieval challenge.

Intelligent surveillance

As LU stations are modernised more cameras are installed, in turn increasing the number of images that are recorded and potentially requiring reviewing by LU control room staff or the BTP. With the threat of terrorism ever present LU staff are required to remain vigilant for suspect packages and suspicious behaviour.

These tasks are secondary the primary duty is to manage the safe operation of the station whilst helping the customers on their journey. Video Analytics (VA) is the automatic analysis of CCTV images to create useful information about the video content.

VA can be applied to a range of applications including intruder detection, left packages and target tracking etc. Video analytics is used to create 'metadata' from each frame of video generated by a given camera. A number of metadata standards exist but MPEG7 is one of the most commonly used. VA works by breaking down CCTV images into their component parts, covering both 'static' background shapes and moving foreground objects. Information on each object is filtered by the software into its position, size, direction of motion, time in view etc.

Platform to Train Interface CCTV / Mirrors

The Platform to Train Interface (PTI) is a particularly hazardous part of the station. It is seen as a top-event risk for LU. Injury and fatality statistics are routinely monitored within LU and by the HMRI. Numerous (risk reduction) measures are used to ensure the risks to customers whilst boarding / alighting from the train or waiting on the platform is driven down to As Low As Reasonably Practicable (ALARP).

These include:-

- OPO (One Person Operation) CCTV / Mirrors
- Platform Markings (Yellow Line);
- Platform Lighting;
- Platform Barriers;
- Platform warnings (Audio & Visual)
- Platform Passenger Emergency Alarm;
- Train PA warnings
- Train Passenger Emergency Alarm (PEA);
- Tactile Paving / Slip resistant surfaces.

Of the risk reduction measures listed above, the OPO CCTV and Mirror surveillance systems provide the train operator an opportunity to detect that customers are clear of the train along the complete Platform Train Interface. In-Cab CCTV is capable of providing the train operator with pre-arrival and post-departure views of the platform to train interface.

Fixed OPO platform CCTV / Mirrors cannot fully provide this information. Both of these types PTI surveillance systems are safety systems and are designed to take into account the PTI environment and human factor issues.

3.1.5 Customer & Control System Information

These systems are used to provide real time information both visual and audible to both customers and LU staff to directly manage and assist with the operation of the railway network. Systems include Public address (PA), Passenger Help Points (PHP), Visual Electronic Information Display systems (VEIDS), Breakdown Broadcast Message Service (BBMS) and Clocks.

LU operational staff need to be regularly updated with service status information including real time incidents. This would be to ensure the efficient operation of the railway to desired service levels. The benefit to customers would be to make informed decisions to better plan their journey from start to finish.

Customers will continue to seek information directly from railway staff or indirectly from LU information boards / displays, Public address, Information Help Points, when on the LU network. Customers about to start a journey can gain network status information from various media channels including radio, television, internet enabled Personal Computers and mobile telephones.

Poor or no customer information leads to frustration for both customers and front line LU staff. In extreme situations this can lead overcrowding in stations as customers who have not checked the status of the network before starting their journey are not given an opportunity to re-plan an alternative journey to their destination, before arriving at the station.

The DDA (Disability Discrimination Act) 1995 has raised the profile of requirements of the mobility-impaired passengers (especially aurally and visually impaired) the adequacy of all systems can be tested for all passengers. Their needs are more demanding than those of able-bodied passengers.

3.1.5.1 Public Address & Voice Alarms (PAVA)

PAVA systems are installed in sub-surface and tube stations primarily for the safe evacuation of customers from the station in emergencies. In this scenario the system is used in conjunction with CCTV to monitor and manage the evacuation. The PA is used to warn customers on or near the PTI about oncoming and departing trains and of 'minding the gap' if one exists at the station. The provision of real-time or recorded messages that are either service related or part of LU corporate policies is secondary.

For this reason, if at stations close to private homes, LU receives a significant number of PA complaints, this secondary function may be limited or disabled under a noise abatement. The frequency and times of the PA broadcasts may also be time restricted.

PA messages can be live or Pre-recorded. Live messages are used mainly for control and management of incidents and emergencies. Live and pre-recorded messages can be made locally at the station or remotely from a Line Control Centre. Remote broadcasts are referred to as "Long Line" PA (LLPA). These latter broadcasts may be limited or banned on surface sites due to noise complaints. Pre-recorded messages are mainly used to reaffirm service status, corporate information and where applicable; Platform safety messages.

The Station PA comprises of multiple "zones". Each zone is a specific area on the station. Any PA announcement point physically located in a zone can only address that zone. PA broadcasts from the Station Control Room can be routed to any or all zones. Long Line PA broadcasts are normally limited to platforms only. The PA system is configured so that it's various inputs live and pre-recorded, local and remote have preset priorities. In general emergency inputs have the highest priority. Emergency broadcasts live or pre-recorded are also all-zone.

LU PAVA systems are linked to the station fire alarm system as required by Fire safety regulations and BS 5839-8:2008, Fire detection and alarm system for buildings. This ensures that the EDVA (Emergency DVA) can automatically initiate a 1st stage (alert) 'Inspector Sands' and 2nd stage (evacuate) messages if the fire alarm panel detects two alerts within one fire alarm zone.

Sub-surface station (fire regulation compliant) Public Address systems were first installed in 1991 as a result of the recommendations made in the Desmond Fennell report into the LU Kings Cross station fire of 1987.

3.1.5.2 Radio Public Address (RPA)

Station staff are provided with RPA microphones so that they can make station platform announcements from any part of the platform within the range of the station announcement point aerial. This gives staff the flexibility of moving to a point where they may have a better view of trains and the PTI. The RPA microphone gives station staff the opportunity to provide a better customer service.

RPA microphones operate at license exempt frequencies circa 850MHz. These require a master frequency plan and each unit may only be used on a dedicated platform. The station infrastructure has an influence on the RPA performance.

3.1.5.3 Public Address - Performance Metrics

The audio performance of PA systems is measured using two metrics;

1. Audibility
2. Intelligibility

Audibility

PA systems audibility is a measure of the 'loudness' of PA messages. Audibility is measured as a sound pressure level (SPL) in decibels. The reference level is the human hearing threshold (20µPA). Audibility is normalised to human hearing using 'A' weighting as defined in IEC 61672:2003.

Setting of audibility levels in PA systems needs to take into account the range of ambient noise levels that are likely to exist during broadcasts. PA audibility requirement is stated in LU standards as 10dB (A) above ambient noise in line with BS 5839-8 et al. This is relaxed for surface stations near residential properties. Noise complaint likelihood is assessed against BS4142.

The limit for audibility levels at surface sites is set by the risk of noise complaints. At sub-surface/tube sites the limit is set by health and safety-noise regulations and customer complaints!

Typical SPL's at surface sites (depending on risk of noise complaints) range from 60 –70dB (A). For sub-surface stations the range is typically 68-78dB (A).

Intelligibility

Speech intelligibility is a measure of the clarity of the PA message. The LU standard for intelligibility is 0.7 CIS (Common Intelligibility Scale). An equivalent STI (Speech Transmission Index) value of 0.5 is also acceptable. CIS and STI are dimensionless numbers between 0 and 1. Perfect intelligibility is denoted by 1 and no intelligibility by 0.

The rational for using CIS is that it enables other intelligibility metrics such as %ALcons, STI to be normalised to the CIS scale. Conversion from STI to CIS is given by;

$$CIS = 1 + \log_{10}(STI) \qquad [15]$$

Normalised CIS or measured STI can be subjectively assessed as tabulated below

CIS Range	STI Range	Subjective intelligibility
≥ 0.9	≥ 0.8	Excellent
0.79 – 0.89	0.61 – 0.79	Good
0.65 -0.78	0.45 – 0.6	Fair
0.54-0.64	0.35-0.44	Poor
<0.54	<0.35	Unacceptable

3.1.5.4 Passenger Help Point Systems (PHP)

Trial Help Points systems were introduced at Oxford circus station around 1987. The concept was extended to the south end of the Northern Line as one of a number of measures to reduce crime.

PHP's are ruggedized intercom systems that provide an audio interface between LU customers and the station control room (SCR). PHP's are strategically located through-out the station including, Ticket halls, platforms, lifts, concourses, passageways etc. such that customers are no more than 30m from a PHP. Two types of PHP's are installed on LU stations;

1. Information and Emergency
2. Information, Emergency and Fire alarm

PHP's fitted with a fire point are installed (normally) at tube and subsurface stations PHP's allow customers to enquire about routine information or request help in emergencies from LU station staff. If routine calls are not acknowledged within a predefined time the caller gets a 'pre-recorded busy message'.

In emergencies failure to acknowledge within 20 to 30 seconds causes the call to be routed to the BTP control room or other designated (staffed) location. Each PHP is monitored by a CCTV camera. The camera view is switched through to an SCR incident monitor during PHP emergency operation. Both emergency video and audio are recorded, the former at (25 fps).

All LU PHP's are easily recognisable to customers due to standardisation of physical features, positioning and dimensions via LU customer standards. For SMS stations the PHP is part of an integrated system. Hearing impaired customers can use the PHP facility via an audio frequency inductive loop (AFILS). The AFIL is linked to the PA so that hearing impaired customers can listen to PA messages.

3.1.6 Real Time Information

Outside LU environment

Dissemination of real-time information to passengers outside the LU environment has changed considerably in recent years. The traditional methods included broadcasts via television and radio media to keep passengers informed ahead of starting a journey.

This practice has been updated over the last 6 - 8 years with the wide spread availability of internet in public places particularly Wireless internet (Wi-Fi). TfL service information web pages are updated regularly. Therefore passengers with access to 'open' Wi-Fi hotspots, GPRS / Edge (2.5/2/75 G) or better mobile services can easily access service information before entering the LU network. Access to high speed mobile services enables streaming of live travel updates.

Within LU network

Real-time information is available to passengers already in the LU network in multiple formats.

1. Audible PA updates in the train via the driver or pre-recordings for planned works

2. Station PA broadcasts from station operations room or the Line control room.

3. Train arrival information via variable electronic information boards (VEID) / Dot matrix displays.

4. Service status information via Electronic service updates boards (ESUB)]

3.1.7 Conclusions

1. Normal service operation is reliant on high availability Communication systems in particular the Integrated connect radio and transmission network

2. Communication systems are vital in the degraded mode for providing reduced service levels and aid service recovery and in emergency modes for the safety of LU customers and its Infrastructure

3. Delivering complex projects and maintenance services presents LU with a number of system level and whole-life problems

4. These problems can be managed using a number of strategies;

    a. ensure the right balance between retaining knowledge expertise against outsourcing

    b. ensure decision support is commensurate with the service delivery risks

    c. Develop appropriate accreditation/ competent management processes

    d. apply systems engineering principles throughout asset lifecycle

    e. ensure system designs are based on the asset whole-lifecycle

3.1.8 Current Developments/ Future Strategies

Developments

1. TfL is funding the installation of Wi-Fi networks at 120 stations in readiness for the London Olympics.

2. LU is trialling IP CCTV to assess benefits

3. Dynamic ambient noise sensors are being trialled in difficult PA environments to minimise noise complaints

4. The Connect core network is being upgraded to include an STM-64 third fibre ring to secure higher future capacity requirements

Future Strategies

Interoperability is significant problem when upgrading communication systems over different time-periods using different suppliers. To minimise this risk LU should ensure;

- Continued use of open standards

- Continued use of COTS

- Use of IP networks to communication services

- Explore developing technologies with potential applications to LU communications including;

    - Nanotechnology [11]
    - Video storage and accessing strategies
    - Integrated customer information delivery
    - Integrated Command & Control
    - Artificial & Machine Intelligence applications
    - Compact backup power storage technology

- Explore the use intelligent applications in key Communication system services

- Develop an integrated suite of Telecoms standards and Manuals of Good Practice based on core LU engineering and service requirements

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