DESIGN OF WIRELESS COMMUNICATION SENSING NETWORKS FOR TUNNELS, TRAINS AND BUILDINGS

S. K. Palit

School of Engineering and Advanced Technology

Massey University, Wellington, New Zealand

e-mail: s.palit@massey.ac.nz

and

Stuart. Bickerstaff and Chris Langmaid

Ambidji Group-Telecommunications, 493 St Kilda Rd, Melbourne, Australia

Abstract—This paper deals with the various assumptions used in the design and analysis of distributed antenna system (DAS) for trains, tunnels and in-building wireless radio coverage. The design includes handover overlap design, base station connectivity, signal reticulation using splitters, couplers, bi-directional amplifiers, attenuators, discrete antennas, radiating cables and opto-electric couplers etc. It is found that signal strength, noise, intermodulation calculated for the up and down links are in compliance with the given specifications and satisfy the required system margin. Our system specifications based on TETRA (Terrestrial Trunked Radio) ensures that the received signal is at least 5 dB higher than the TETRA dynamic sensitivity level and yields 95% coverage of all the used areas.

Index Terms—antenna, signal distribution, wireless network, uplink, downlink, system margin

I INTRODUCTION

It has been found from the recent literature survey [1- 13] that no proper design tools have yet been developed for indoor wireless communications. As cellular systems are operated today, in-building communication is provided by transmitting radio signals from cell sites to portable handsets inside buildings which requires the transmitted power to be about 20 dB stronger than that for the ground mobile communications in order to penetrate into or out from a building. The coverage of the portable units is not two-dimensional but three-dimensional. When a radio channel penetrates from outside into a multi-floor building, this particular channel can serve only one user who is located on one floor. The other potential users on different floors can not use the same channel. In-building communications need enormous radio channels which the current cellular system can not provide.

Walker [10] found that building penetration loss decreased at a rate of 1.9 dB per floor from the ground level up to the fifteenth floor and then began increasing above the fifteenth floor. The increase in penetration loss at higher floors was attributed to shadowing effects of adjacent buildings. There are many technologies, such as third and fourth generation (3G and 4G) cellular, TETRA (Terrestrial Trunked Radio) and WLAN (Wireless Local Area Network) systems that have increased the challenges and demands for cost-effective indoor wireless communication system design. Distributed Antenna System (DAS) can provide excellent coverage compared with single antenna or penetration into buildings from outside macro cells [1-6]. The signal power is distributed using filters, splitters, attenuators, bi-directional amplifiers, discrete antennas and radiating cables, optical transceivers, low loss coax cables, and optical fibers. The radiated power is controlled on each floor of the building to keep the system within the health and safety limits, as recommended in [14] and to minimize the signal power that leaks out of the building.

This paper describes various assumptions used in the design. The study presents design and analysis of the radio system coverage consisting of handover overlapping, base station connectivity, signal reticulation using designed distributed antenna system, uplink and downlink signal budgets in indoor and tunnel environment. Since the design band was 390 MHz to 850 MHz, low loss radiating cables were mainly used. At some points where large area coverage was required, two discrete antennas, one for 400 MHz band and the other for 850 MHz with band pass filters feeding each antenna were used.

II DESIGN ASSUMPTIONS

A. Modified Keenan Motley Model

Coverage prediction modeling for in-building coverage has improved over recent years [1 - 6]. Models are generally split into two types, the power law models and the site specific models. If drawings of the building or complex are available, a site specific model is useful. An example of a site specific model which incorporates both penetration into a building and in-building losses is the modified Keenan-Motley site specific model [11], where:

$$\text{Path Loss} = L + 20 \log d + k F + p W_i + We \text{ (dB)} \quad (1)$$

where, L = mean path loss to the building parameter (dB), d = the distance into the building (meters), k = the number of floors between Tx and Rx, F = the floor loss factor (dB), p = the number of interior walls between Tx and Rx, W_i = the interior wall loss factor (dB), We = the external wall loss factor (dB). Since in our system design, antennas or radiating cables within the building are used, general penetration loss into the building is not required. When the coverage into rooms is provided by radiating cables, the above model is modified slightly. The term L (free space loss from the antenna) is removed because the coupling loss figure used in the link budgets represents the equivalent loss at a distance of 2 m from the radiating cable. As the coupling loss is measured at 2 m from the cable and in practice the room may be further away from the radiating cable, a correction term is added for the additional loss. Again, the propagation loss from a radiating cable is proportional to 1/d rather than $1/d^2$, therefore, the additional loss with distance is less than the model. The new path loss for the radiating cable is:

$$\text{Path Loss} = 10 \log (d/2) + k F + p W_i \quad (2)$$

The free space path loss (FSL) is given by:

$$FSL = 20 \log f + 20 \log d + 32.4 \quad (3)$$

where, f = the frequency in MHz and d = the distance in km. The assumptions for wall penetration loss used in the calculation of the link budgets are [7]: 190 Solid Blockwork: 10 dB, 225 Solid Blockwork: 12 dB, Reinforced Concrete wall: 18 dB, and Glass Wall/Windows: 3 dB

B Rayleigh fading and Doppler Shift

Different paths may exist between a base station (BS) and a mobile set (MS) giving rise to a number of partial waves arriving with different amplitudes and delays. Since the MS will be moving, a Doppler shift is also associated with each partial wave, depending on the MS's velocity and the angle of incidence. The delayed and Doppler shifted partial waves interfere at the receiver causing frequency and time selective fading on the transmitted signal. When system bandwidth and propagation path lengths are sufficiently small, which is the case for TETRA, the resulting frequency and time selective fading process can be simulated by a simplified propagation model. Such a model exhibits only a few discrete paths which are independently fading. For practical channel simulation, stationary Gaussian processes with a power density spectrum equal to the classical Doppler spectrum (Clarke's model) are assumed.

C TETRA Dynamic Sensitivity Model

The TETRA standard caters for the two main cases of stationary users and moving vehicles at speeds up to 200 km/h through various terrains. The dynamic sensitivity model is typical of built-up areas for situations where there is no LOS path but some reflections from large buildings. For our system design, users are assumed to be moving and therefore the dynamic sensitivity limits apply. It is assumed that the received signal is at least 5 dB higher than the TETRA dynamic sensitivity limit as shown in the Table I.

D Noise

It is assumed that our in-building mobile coverage system has 25 kHz channel spacing. The noise floor of a receiver is calculated as the thermal noise plus the receiver noise figure. The 3 dB bandwidth is assumed as the reference bandwidth for the receiver IF stages. For special services such as Police, Ambulance, Security systems this bandwidth can safely be assumed to be 18 kHz. This results in a thermal noise figure of -131.44 dBm. When considering digital radio systems, symbol-energy-to-noise ratio (E_b/N_o) is equivalent to carrier–to-noise ratio (C/N) but only when the receiver filter's equivalent noise bandwidth has the same value as the bit/symbol rate. With the π/4 DQPSK (differential quaternary phase shift keying) modulation each phase transition represents a dibit, therefore, in TETRA system the symbol rate is half the gross bit rate of 36 kbps or 18 k symbols per sec. Within the TETRA specification for the assumed noise figures of 6.4 dB for a BS and 9.4 dB for a MS, the E_b/N_o of 10 dB for static and 19 dB dynamic conditions results at the reference sensitivity level. For example, the base station dynamic reference sensitivity is derived from: Receiver dynamic sensitivity = E_b/N_o + NF - kTB = 19 dB + 6.4 – 131.4 dBm = -106 dBm (Table 1) which highlights TETRA's ability to operate with a carrier-to-noise ratio of 19 dB. The link budget calculations are based upon the assumptions shown in Table II.

Table I TETRA sensitivity vs specifications

Equipment type	Static sensitivity	Dynamic sensitivity	Our system specifications
Base station	-115 dBm	- 106 dBm	- 101 dBm
Mobile/handportable	-112 dBm	- 103 dBm	- 97.5 dBm

Table II

Base Stations transmit power (for buildings-general uses)	48.5 dBm
Base Stations transmit power (for Security)	40 dBm
Base Stations transmit power (for Police)	44 dBm
Base Stations transmit power (for Fire Service)	49.5 dBm
Handheld mobile transmit power (for buildings-general uses)	30 dBm
Handheld mobile transmit power (for Security)	30 dBm
Handheld mobile transmit power (for Police)	30 dBm
Handheld mobile transmit power (for Fire Service)	30 dBm
Train Penetration Loss (from leaky coax cable)	35 dBm
95% Rayleigh Fade Margin	11 dB
98% Rayleigh Fade Margin	15 dB

From CCIR Report 258-4 [14-15] it is found that the noise level in the frequencies of interest is extremely low, that is, at our design frequencies, such as: at 850 MHz, the noise level is = < 1 dB relative to kTB; at 450 MHz, the noise level equals to 5 dB relative to kTB and at 390 MHz, the noise level equals to 6 dB relative to kTB. Considering the case of noise pick up by the radiating cable, the coupling loss of the cable (>60 dB) ensures that any noise coupled through radiation into the cable is at negligible levels with respect to kTB. Considering the case of man made noise picked up by a discrete antenna in the building, we must consider the gain of the antenna and the loss in the cabling and splitting system to the antenna. Hence, a typical link gain by the man made noise at 390 MHz is: 6 dB (noise level relative to kTB) + 2 dB (receiving antenna gain) – 7 dB (assuming minimum two signal splitters each 3.5 dB loss) – 1.5 dB (cable loss) = -0.5 dB relative to kTB. Therefore, it can be assumed that man made noise at the receiver multicoupler is always below the inherent thermal noise and is therefore negligible in the noise analysis.

III DISTRIBUTED ANTENNA SYSTEM (DAS)

A. Handover Overlap Design

The handover process requires coverage overlap from base station to base station. For a train tunnel sufficient mobile coverage overlap is provided calculating train's maximum speed of 160 km/h (45 m/s). The TETRA air interface defines the parameters used in the algorithm for handover to ensure that level and time hysteresis are included, thus preventing the 'ping-pond' effect of repeated handovers at marginal areas. The key parameters of this algorithm are the threshold level at which a handover is initiated and time over which handover criteria must be stable which is defined as 5 seconds. The handover threshold is a configurable parameter. The antenna network must provide stable overlap conditions for a period of > 5 seconds to allow handover to occur correctly. At a maximum speed of 45 m/s, 5 seconds corresponds to a distance travelled of 225 m.

Where a handover is to be performed in tunnels covered by leaky feeders, the antenna system is designed to provide an extended coverage of 225 m from each base station, thus giving an effective RF overlap area of 450 m at the handover location. It should be noted (Table 1) that the down link signal level requirement of the main building system is -97.5 dBm where the dynamic receiver sensitivity of a TETRA mobile system is -103 dBm, that is, 5.5 dB below. This difference effectively increases the available overlap area as the mobile will continue receiving down to the TETRA sensitivity level, thus providing an inherent margin. The longitudinal attenuation of radiating cable is 4.3 dB/100 m, which increases the total coverage overlap by 5.5/4.3 x100 = 128 m. This gives a total overlap distance of 353 m per base station, giving a total RF overlap area of 706 m (Fig. 1).

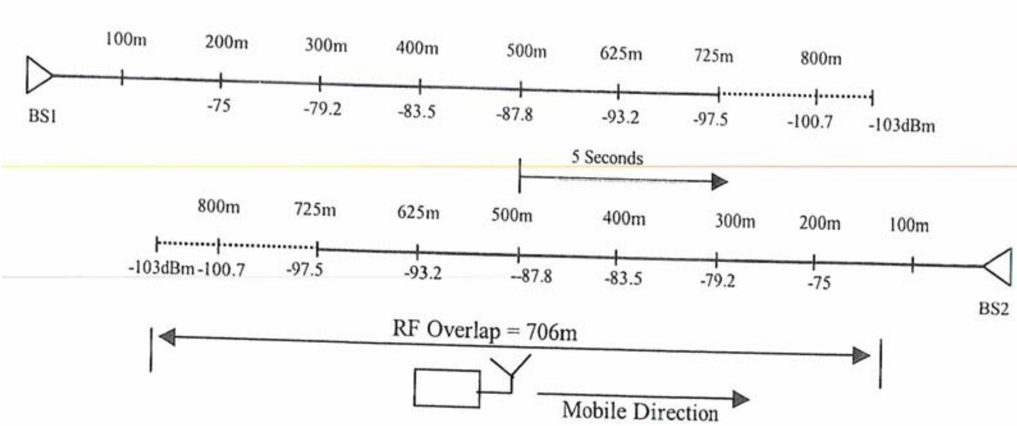

Figure.1 Handover overlap in a typical tunnel environment

B. Handover Design in Open Areas

Assume that a particular section of track covered by an antenna is designed to provide a signal level of – 97.5 dBm at the coverage boundary which is 1 km from the antenna (Fig. 2). The free space loss over 1 km at 850 MHz is 91 dB. In order to provide a smooth handover the mobile must be able to receive carrier from the old cell for 5 secs whilst moving into the new cells. At the maximum train speed this corresponds to a distance of 1.225 km from the antenna. The free space loss over 1.225 km is 93 dB, therefore the received signal level has dropped by only 2 dB over the worst case handover distance. The received signal level is still far above the sensitivity of the mobile receiver (Table 1). In practice, the mobile will receive the carrier from the old cell for over

500m into the new cell before the receiver sensitivity limit is reached, again providing an inherent design margin for smooth handover (Fig. 2).

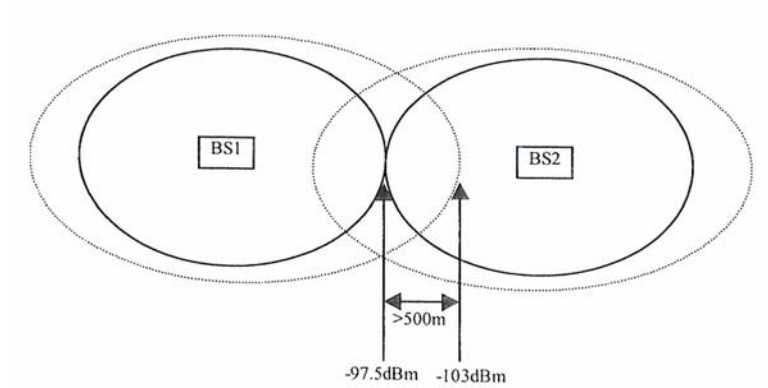

Figure 2 Handover overlap in open areas

Fig. 3 shows a typical distributed antenna system designed for indoor radio coverage of a section of a multistory building. The multi network combiner unit (MNCU) in Fig. 3 combines the networks into four identical outputs for connection to the distributed antenna system. Table III shows some calculated uplink received signal strength from the mobile at site B. The estimated calculations yield a system margin of 10.8 dB.

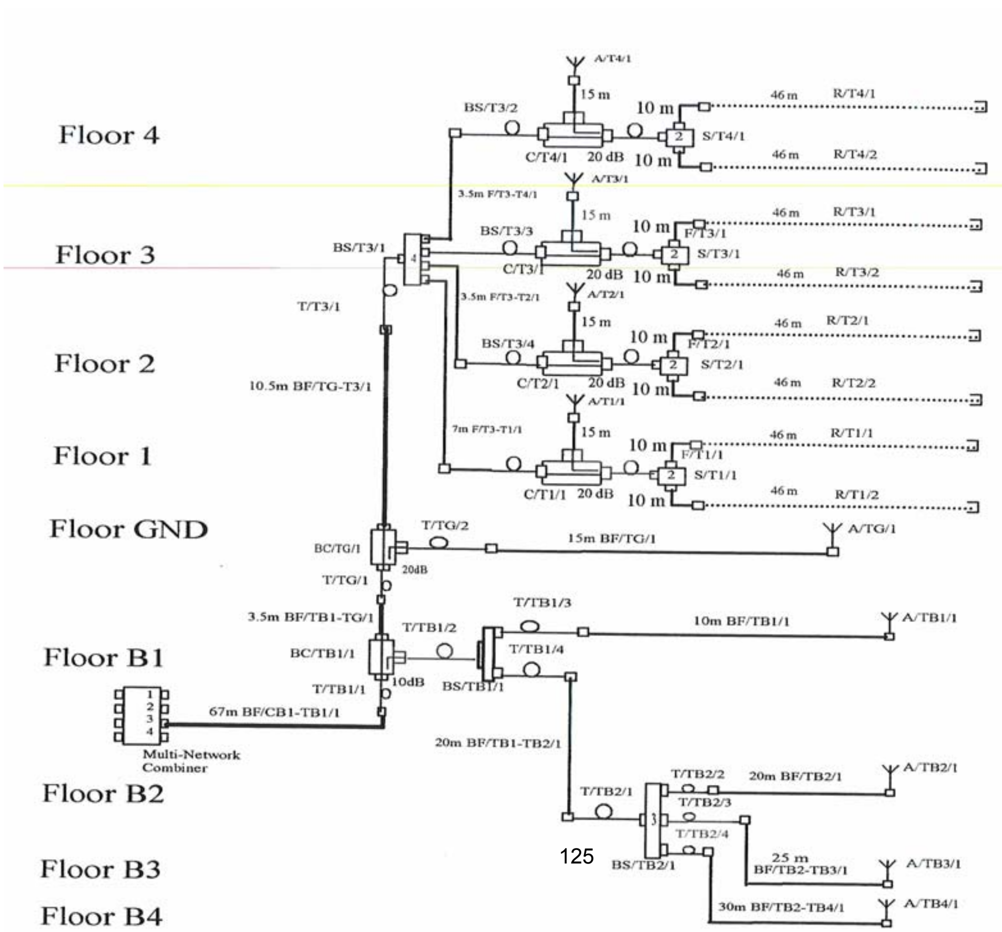

Figure3 A typical one line distributed antenna network for a section of a multistory building

Table III

Site B	Gain (G)	Loss (L)
Duplexer Loss in dB		1
Feeder to Antenna in dB		3
Rooftop Antenna Gain in dBi	6	
Site B Antenna System net Gain/Loss in dB	2	
Tx Output Power at Site B repeater in dBm	44	
Effective Isotropic Radiated Power (EIRP) from Site B	46	
Measured Received Downlink Signal Strength at Site A (dBm) from Site C	-97	
Estimated Height Gain due to Mounting Antenna on Site A Roof (1.5 dB per floor, 9 floors) in dB	13.5	
Total Path Loss from Site C to Site A in dB (-97-46+10.5 = 132.5)	129.5	
Tx Output Power Site A in dBm	40	
Feeder to Antenna Loss in dB		1.5
Rooftop Antenna Gain in dBi	2.15	
Effective Isotropic Radiated Power from Mobile Radio at Site A in dBm	40.65	
Path Loss in dB		129.5
Site B System Antenna Gain in dBi	2.0	
Received Signal Level at Site B in dBm (40.65 -129.5 +2.15 = - 90	-86.7	
Specification Limit in dBm at Site B repeater in dBm	-97.5	
Design Margin (dB)	10.8	

IV SIGNAL RETICULATION

Fig. 4 shows the top level design for the POI (Point of interconnect) for the KSR, Hong Kong Railway station. Each component of the POI has been separately designed for seamless communications. Details of the designed components are deliberately not included in this paper for avoiding voluminous size of the paper. Figs. 5 -8 illustrate the hybrid combiner arrangement used for KSR with 4 TETRA transceivers and 1 Fire Service Division (FSD) transceiver at 850 MHz and for the Hong Kong Police (HKP) system at 450 MHz respectively.

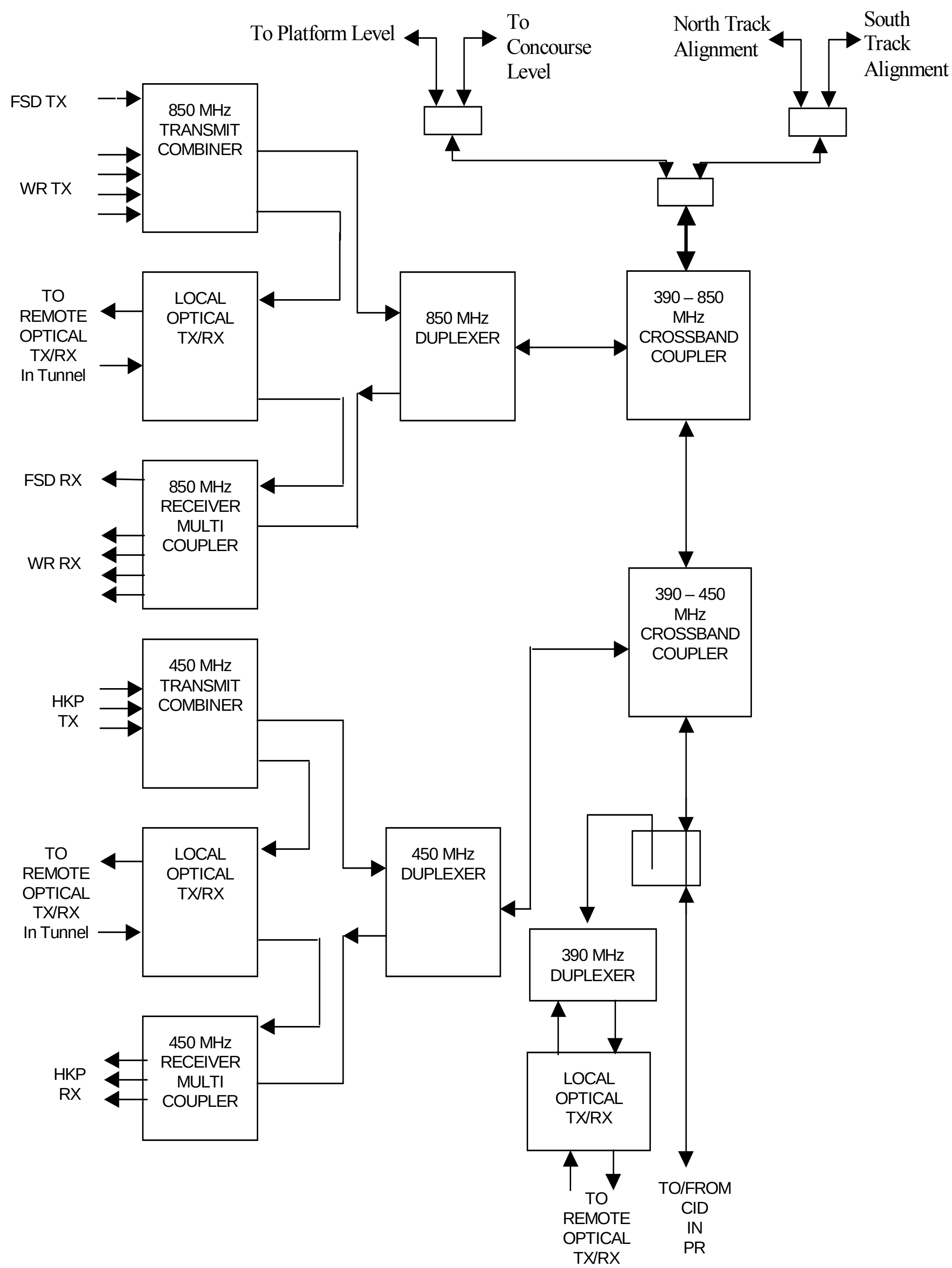

Figure 4 Point of Interconnect (POI)

The design of the Tai Lam Tunnel radio coverage network for West Rail, Hong Kong Police, CID and Fire Services Systems is shown by Fig. 9. It includes the design of the radiating network through the tunnel and also that of the two ventilation buildings (HKVB and CKVB) at either end of the tunnel. The overall arrangement drawing (Fig. 9) shows the position of each major active and passive device in the tunnel together with its chainage. The estimated radio coverage at 850, 450 and 390 MHz for both the North Direction (TWW to KSR) and the south direction (KSR to TWW) are shown in the figure.

From this drawing detailed link budgets have been made both for the uplink and downlink at each of the worst case points of the radiating system. The calculated signal levels have been found to be above the minimum specified values to achieve coverage into each of the required coverage areas in the buildings and the tunnel.

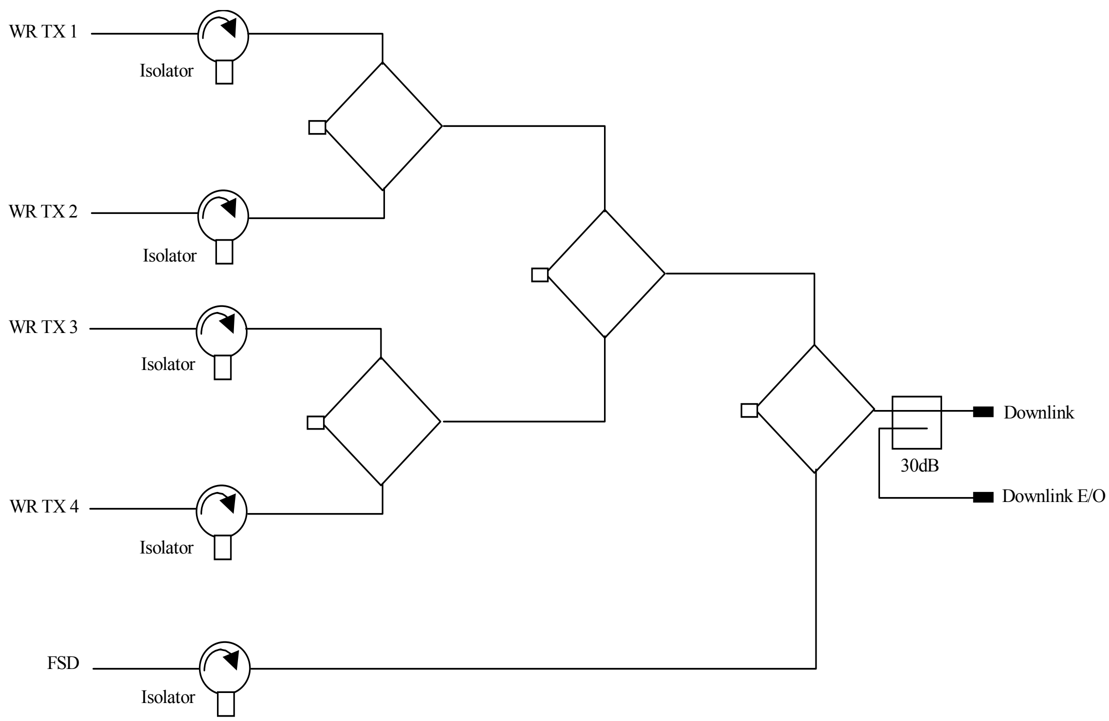

Figure 5: 850 MHz Transmitter Combiner
(WR TX = West Rail Transmitters, FSD = Fire Service Division)

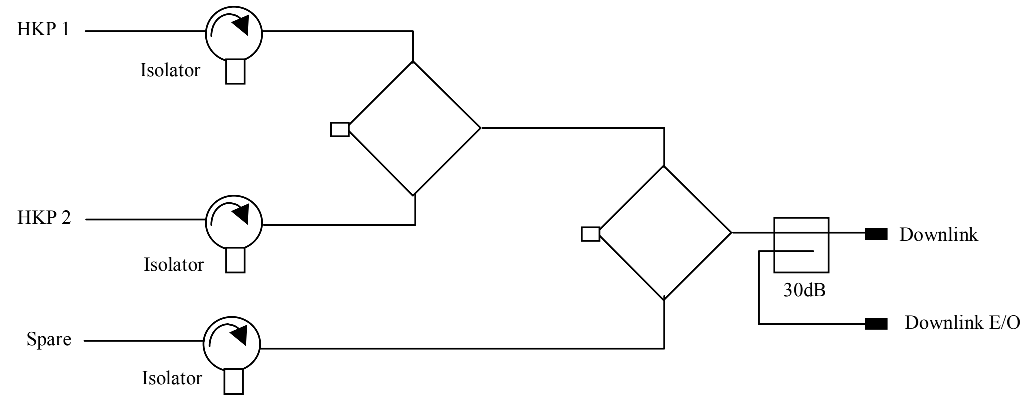

Figure 6: 450 MHz Transmitter Combiner (HKP = Hong Kong Police)

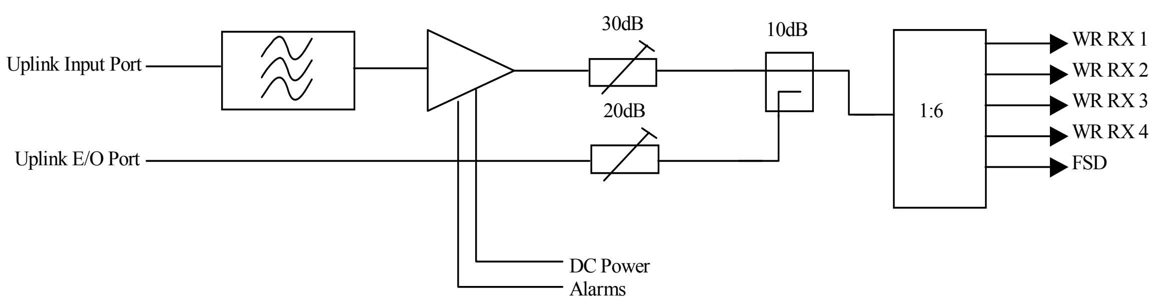

Fig. 7: 850MHz Receiver Multicoupler

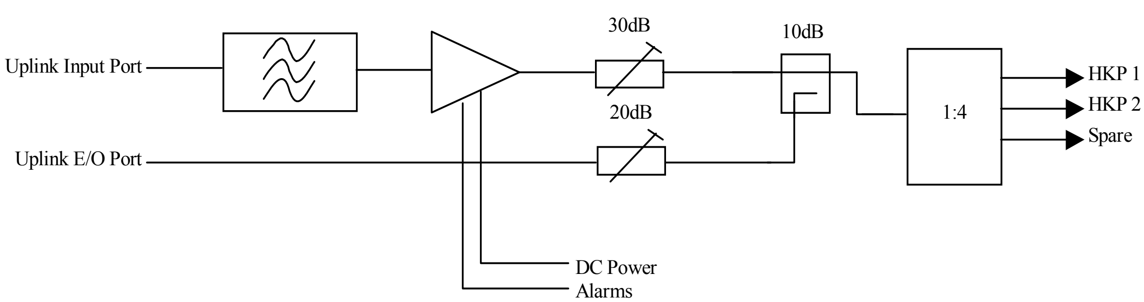

Fig. 8: 450MHz Receiver Multicoupler

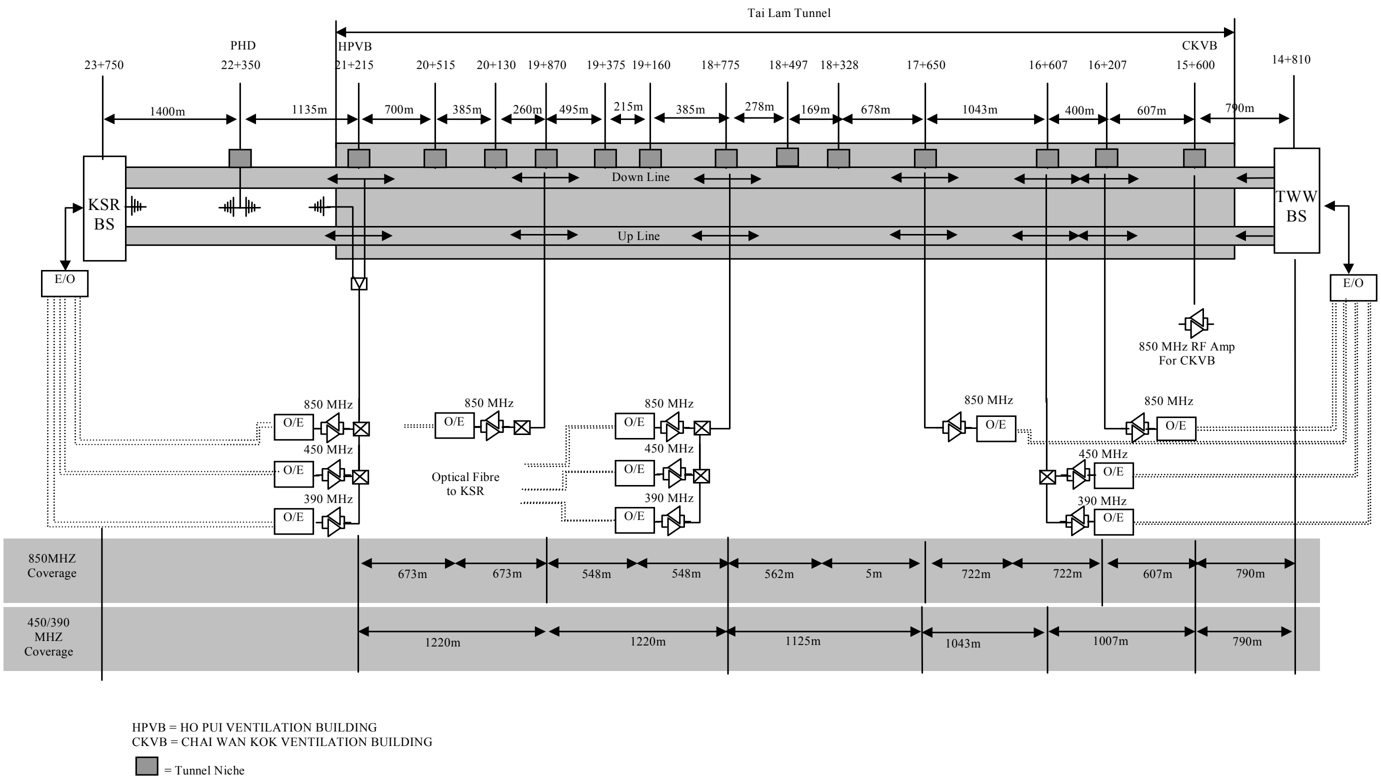

Fig. 9: Radio coverage design for Tai Lam Tunnel, Hong Kong.

V LINK BUDGET ANALYSIS

The following link budgets analyses (Tables V and VI) illustrate both the uplink and the downlink budgets taking into consideration all the amplifiers, antennas, RF combiners gain, the splitters, coaxial cables, couplers, radiating cables and train penetration losses in the tunnel at 850, 450 and 390 MHz. It is seen that the link budgets satisfy the required operating system margin. Similar uplink and downlink signal and noise analyses have been made for all the radiating cables and discrete antennas at every point to be sure that the design system satisfy the required system margin for in-building and tunnel radio coverage.

Table V

Downlink {From BS TX to Handportable inside train in tunnel}
Location : 18+775 North, Fed by KSR

1. Assumed In-band Frequency, *fMHz*		390MHz		450MHz		850MHz	
2. Non-radiating Coaxial Cable Attenuation Specification, *LN*		2.48	dB/100m	2.6	dB/100m	3.7	dB/100m
3. Estimated Run Length of Non-radiating Coaxial Cable, *DN in Metres*		30		30		30	
4. Radiating Coaxial Cable Attenuation Specification, *LR*		2	dB/100m	2.2	dB/100m	4.3	dB/100m
5. Estimated Run Length of Each Arm of Radiating Coaxial Cable, *DR in Metres*		1220		1220		548	
		Gain (G)	Loss (L)	Gain (G)	Loss (L)	Gain (G)	Loss (L)
(a)	Tx Output Power into POI (dBm)	40.00		44.00		49.00	
(b)	Police Room to TER Loss (CID only)		2.50		0.00		0.00
(c)	Combiner Gain/Loss (dB)		0.00		7.00		10.50
(d)	Coupler Loss (feed to optical transceiver)		30.00		30.00		30.00
(e)	Duplexor (CID only)		1.00		0.00		0.00
(f)	RF Combiner System Gain(G) / Loss (L) (a) to (e)	40.00	33.50	44.00	37.00	49.00	40.50
(g)	Carrier Power at Optical Transceiver Master Unit RF Input (dBm)	6.50		7.00		8.50	
(h)	Carrier Power at Optical Transceiver Master Unit RF Input (dBm)	6.50		7.00		8.50	
(i)	Optical Transceiver Master Unit Pad Setting		14.00		14.00		16.00
(j)	Optical Splitting Loss (Fibre Master Unit)		6.00		6.00		12.00
(k)	Fibre Loss in link to Remote		4.00		4.00		4.00
(l)	Connector/Splice Loss		2.00		2.00		2.00
(m)	Downlink Gain of Remote RF amp	60.00		60.00		60.00	
(n)	Downlink RF amp Pad Setting		3.00		4.00		8.00
(o)	Total System Gain*(G)* /Loss*(L)* *{Sum of (h) to (n)}*	66.50	29.00	67.00	30.00	68.50	42.00
(p)	RF Output Power from Remote Fibre Unit (dBm)	37.50		37.00		26.50	
(q)	RF Output Power from Remote Fibre Unit (dBm)	37.50		37.00		26.50	
(r)	RF Splitter Loss		7.00		7.00		7.00
(s)	Cross Band Coupler Loss		1.00		1.00		0.50
(t)	Non-radiating Coaxial Cable Attenuation Loss [0.01*LN* x *DN*] (dB)		0.74		0.78		1.11
(u)	Radiating Coaxial Cable Attenuation Loss [0.01*LR* x *DR*] (dB)		24.40		26.84		23.56
(v)	Radiating Coaxial Cable 95% Coupling Loss (dB)		77.00		71.00		68.00
(w)	Train Penetration Loss		8.00		8.00		8.00
(x)	Total System Gain*(G)* /Loss*(L)* *{Sum of (p) to (w)}*	37.50	118.14	37.00	114.62	26.50	108.17
(y)	Net Received Downlink Power, *PDL = G - L in dBm*	-80.64		-77.62		-81.67	
(z)	Minimum Received Downlink Power Required, *FDL in dBm*	-87.00		-87.00		-97.50	
(a1)	System Operating Margin = *PDL - FDL*	6.36		9.38		15.83	

Notes
(k) Fibre Loss = 0.38dB/km over 5km. RF Loss is twice Fibre Loss.

Table VI

Uplink {From Handportable inside train in tunnel to RX}
Location : 18+775 NTH,Fed by KSR

1. Assumed In-band Frequency, *fMHz*		390MHz		450MHz		850MHz	
2. Non-radiating Coaxial Cable Attenuation Specification, *LN*		2.48	dB/100m	2.6	dB/100m	3.7	dB/100m
3. Estimated Run Length of Non-radiating Coaxial Cable, *DN in Metres*		30		30		30	
4. Radiating Coaxial Cable Attenuation Specification, *LR*		2	dB/100m	2.2	dB/100m	4.3	dB/100m
5. Estimated Run Length of Each Arm of Radiating Coaxial Cable, *DR in Metres*		1220		1220		548	
		Gain (G)	Loss (L)	Gain (G)	Loss (L)	Gain (G)	Loss (L)
(a)	Tx Output Power at Handportable(dBm)	30.00		30.00		30.00	
(b)	Train Penetration Loss		8.00		8.00		8.00
(c)	Cross Band Coupler Loss		1.00		1.00		0.50
(d)	Radiating Coaxial Cable Attenuation Loss [0.01*LR* x *DR*] (dB)		24.40		26.84		23.56
(e)	Radiating Coaxial Cable 98% Coupling Loss (dB)		81.00		73.00		70.00
(f)	Non-radiating Coaxial Cable Attenuation Loss [0.01*LN* x *DN*] (dB)		0.74		0.78		1.11
(g)	RF Splitter Loss		7.00		7.00		7.00
(h)	Total Gain(G)/Loss(L)	30.00	122.14	30.00	116.62	30.00	110.17
(i)	Uplink Power at Remote Optical Amplifier Input in dBm (G)-(L)	-92.14		-86.62		-80.17	
(j)	Uplink Power at Remote Optical Amplifier Input in dBm (G)-(L)	-92.14		-86.62		-80.17	
(k)	Gain of Remote Unit	50.00		50.00		50.00	
(l)	Fibre Loss		4.00		4.00		4.00
(m)	Connector/Splice Loss		2.00		2.00		2.00
(n)	RF Combining Loss		3.50		3.50		7.00
(o)	Master Unit E/O Pad Setting		15.00		5.00		0.00
(p)	Total Gain(G)/Loss(L)	-42.14	24.50	-36.62	14.50	-30.17	13.00
(q)	RF Output Power from Master Fibre Unit (dBm)	-66.64		-51.12		-43.17	
(r)	RF Output Power from Master Fibre Unit (dBm)	-66.64		-51.12		-43.17	
(s)	Coupler Loss into RX Multicoupler		20.00		20.00		20.00
(t)	Receiver Multicoupler E/O Pad Setting		0.00		8.00		8.00
(u)	Multicoupler Splitting Loss		0.00		7.00		9.00
(v)	Duplexor Loss (390MHz only)		1.00		0.00		0.00
(w)	CID Link Loss from RF Panel (PR Room) to TER		2.50		0.00		0.00
(x)	Total System Gain*(G)* /Loss*(L)* *(r) to (w)*	-66.64	23.50	-51.12	35.00	-43.17	37.00
(y)	Net Received Uplink Power, *PDL = G - L in dBm*	-90.14		-86.12		-80.17	
(z)	Minimum Received uplink Power Required, FDL in dBm	-101.00		-101.00		-101.00	
(a1)	System Operating Margin = *PDL - FDL*	10.86		14.88		20.83	

Notes
(k) Fibre Loss = 0.38dB/km over 5km. RF Loss is twice Fibre Loss.

VI CONCLUSION

We designed and analysed a wireless communication system using distributed antenna networks in in-building and tunnels environment. Several design specific assumptions were made. Based on those assumptions, uplink and down link budgets, and noise have been studied. Our design, based on TETRA ensures that the received signals satisfy the system requirements and remain above the required system margin. The point of interconnect and its associated multicouplers, filters, transceivers and remote optical transceivers provided necessary desired signals for multiband (850, 450 and 390 MHZ) applications. The designed system has been commissioned and is in use. With some minor modifications, the system can be used for any in-building radio coverage.

ACKNOWLEDGMENT

The authors are thankful to China Motion (Hong Kong), Siemens (Hong Kong) and Ambidji Group, Melbourne for financial support and assistance to execute this project.

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