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Compromise in CDMA Network Planning

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Abstract

CDMA network planning, for example in 3G UMTS networks, is an important task whether for upgrading existing networks or planning new networks. It is a time consuming, computationally hard, task and generally requires the consideration of both downlink and uplink requirements. Simulation experiments presented here suggest that if time is a major consideration in the planning process then as a compromise only uplink needs to be considered.

Keywords: CDMA, Network Planning, Optimization, Simulation

1. Introduction

The past decade has seen the emergence of many computational approaches for cellular network site selection, configuration and dimensioning. Many of these contributions have paid attention to planning wide-area FTDMA systems such as second generation GSM where planning is generally carried out using a downlink transmission model and independent criteria for coverage and capacity, *e.g* [1].

A number of researchers have considered the rather more complex problem of network planning for UMTS networks. Amaldi *et al* ([2-5]) propose a mathematical programming model which accounts for both the uplink and downlink directions as well as for base station configuration issues including location, height, tilt and azimuth. To allow solutions to be sought in reasonable time, approximate solutions are sought via application of the tabu search meta-heuristic. In [6] and [7], Zhang, Yang, *et al.* propose a mathematical framework for UMTS network planning that considers fast power control, soft handover and pilot signal power in the uplink and downlink directions. Again, solutions are sought via the application of meta-heuristics (SA and evolutionary SA). Ben Jamaa *et al.* ([8,9]] propose an approach which employs a multi-objective GA (MOGA) to simultaneously optimize capacity and coverage by adjusting antenna parameters and common channel transmitted powers (antenna locations fixed). A multi-objective fitness function is employed which can consider objectives such as coverage, capacity and cost. The result of the MOGA is a Pareto set of non-dominated solutions.

For third generation systems such as UMTS, the planning problem is significantly more complex than for FTDMA systems due to the dependency between capacity and coverage. The underlying CDMA protocol requires that on each link, a target signal to noise ratio (SNIR) is maintained, and consequently per-link power allocation is required before user service coverage and cell load can be accurately assessed. However, determining this is non-trivial as one user transmission is seen as interference by all other users, making coverage/capacity evaluation sensitive to other users. Transmission power minimization is important and the real-time UMTS system achieves this by fast power control. However for modeling purposes, this is costly to repeatedly simulate because all links are required to frequently re-evaluate their SNIR and adjust power accordingly.

Whitaker R. M. *et al* describe two efficient heuristic algorithms that enable the evaluation of service coverage and cell loading in both the uplink and downlink directions. In this paper, we investigate the application of these heuristics to the problem of cell planning for UMTS networks. The cell planning problem (CPP) is concerned with the selection of *antennae* from a set of *candidate antennae*, and the configuration of these antennae, such that an optimal configuration is achieved. As for the frequency assignment problem (FAP), the CPP has *NP*-complete computational complexity. This dictates that exact solutions to the CPP cannot be attained in practice. Hence we consider a meta-heuristic optimization approach.

The remainder of this paper is organized as follows. Section 2 describes the model and Section 3 provides a brief overview of the uplink and downlink service coverage/load evaluation heuristics. Section 5 outlines the optimization problem and the meta-heuristic employed. A number of test problems are defined in Section 5 and the results and analysis of applying our optimization approaches to these problems can be seen in Section 6.

2. Model

The uplink (UL) and downlink (DL) dedicated channels and the pilot signal is included in our model. Parameters are described in **Table 1**, **Table 2** and **Table 3** and are defined relative to the link direction under consideration.

The terms *cell*, *antenna* and *transmitter* are used interchangeably when describing aspects of coverage. A number of candidate antenna locations are defined for a given region. A planning/optimization process is employed to select and configure antennae based on defined objectives. Discrete *test points* from the region are used to sample service coverage. Each test point is a physical position (expressed in two dimensional Cartesian co-ordinates). Two types of test point are defined in our

Table 1. Global parameters.

Symbol	Description
W	CDMA chip rate.
R_i	Data rate for service *i*.
S_A	Set of all antennas in the working region.
S_{ptp}	The set of covered pilot test points.
S_{stp}	The set of service test points.
O_{stp}	An ordering of the *stp*.

Table 2. Uplink parameters.

Symbol	Description
p_{xy}^{UL}	Received power from *stp x* at a cell *y*.
I_{own}	Total received power from *stp* active in cell *y*.
I_{oth}	Total received power from *stp* active in cells other than *y*.
I_y	Total received power from all active *stp*.
N	Noise power seen at the antennas receiver in an empty cell.
$(E_b/N_o)_{UL}^*$	Target threshold for E_b/N_o ratio at an stp for the dedicated UL channel (service dependent).
$\eta_{UL,y}$	Uplink load at cell *y*.

Table 3. Downlink parameters.

Symbol	Description
$Iown$	Total power received from serving cell (all links and pilot).
$Ioth$	Total power received from all cells other than the serving cell.
α	Orthogonality Factor.
P_n	Noise power (thermal and equipment) seen at a test point.
p_{xy}^{DL}	Power allocated by cell *y* for *stp x* as received at stp *x*.
p_{xy}^{pilot}	Pilot power from cell *y* as received at stp *x*.
$(E_c/I_o)_{pilot}$	Target threshold for pilot E_c/I_o ratio.
$(E_b/N_o)_{UL}^*$	Target threshold for E_b/N_o ratio at an stp for a dedicated DL channel (service dependent).
$\eta_{DL,y}$	Downlink load at cell *y*.
$PtxTotal_y$	Total of allocated transmit powers in cell *y*.
$Ptxmax_y$	Maximum transmit capability of cell *y*.
$\eta_{pilot,y}$	Proportion of $Ptxmax_y$ allocated for pilot signal at cell *y*.

model: service test points (stp) and pilot test points (ptp). The ptp are used to assess pilot signal quality. At an stp, quality of both UL and DL dedicated channels are as sessed for a particular service, which is defined prior to evaluation.

2.1. Test Point Coverage and Cell Load

The pilot signal is transmitted at a proportion $\eta_{pilot,y}$ of the maximum cell power. A *ptp x* is served by antenna *y* when the received energy per chip relative to the total spectral density *Ec/Io* at least meets the target Ec/Io_{pilot}. Letting $I_y = I_{own} + I_{oth}$, then *x* is served if and only if:

$$\frac{p_{xy}^{pilot}}{N+I_y} \geq \left(E_c/I_o\right)_{pilot} \qquad (1)$$

An *stp* is *covered* in a particular link direction if energy per bit relative to spectral noise density *(Eb/No)* at least meets the required target threshold. For an *stp x* connected to antenna *y*, *x* is *UL covered* if and only if:

$$\frac{W}{R_i} \cdot \frac{p^{UL}{}_{xy}}{I_y - p_{xy} + N} \geq \left(Eb/No\right)_{UL}^{*} \qquad (2)$$

In the downlink, for an *stp x* and serving antenna *y*, *x* is *DL covered* if and only if:

$$\frac{W}{R_i} \cdot \frac{p^{DL}{}_{xy}}{I_{own}(1\text{-}\alpha)+I_{oth}+p_n} \geq \left(Eb/No\right)_{DL}^{*} \qquad (3)$$

There are various ways in which cell loading can be assessed. Wideband power-based measurement is used in this model because it directly identifies the resources being allocated. The downlink load at cell *y* is estimated by:

$$\eta_{DL,y} = \frac{PtxTotal_y}{Ptxmax_y} \qquad (4)$$

while the uplink load at cell *y* is estimated by:

$$\eta_{UL,y} = \frac{I_y}{I_y + N} \qquad (5)$$

Note that a *ptp*'s ability to be served depends on downlink cell load. Consequently a *ptp* is covered if and only if it is served when all cells *y* are operating at maximum permitted downlink load $\eta_{DL,y}^{max}$. Covered *ptp* can see the pilot signal independent of traffic and are collectively denoted S_{ptp}.

To ensure that an *stp* can see the pilot signal, it is required that $S_{stp} \subseteq S_{ptp}$. A list O_{stp} of the set S_{stp} is also required to specify the order in which *stp* are prioritized for admission. The ordering is defined based on the received signal strength from the best serving antenna with those with the strongest signal given priority.

3. Evaluation Heuristics

Calculating off-line transmission power for target *Eb/No* attainment on a link requires knowledge of interference levels or equivalently cell loads. However, interference/cell loads depend on per-link transmission powers. This dependency has led to the analytical characterization of the problem [11]. We employ an algorithmic approach which initially over-estimates interference/cell loading and then uses a feedback mechanism to iteratively update and reduce the conservative error. When this feedback mechanism is applied, the heuristic can converge to a state where inaccuracy in power allocation and cell loading is negligible. From this, *stp* coverage and cell loads can be directly obtained.

Detailed discussion of the uplink and downlink evaluation heuristics used here can be found in [10].

4. Optimization Problem

It is assumed that for optimization, the objective is to select/activate and configure (where appropriate) a subset of antennae from the set of candidate antennae such that coverage is maximized for a specified number of active transmitters. After experimentation with a number of meta-heuristics it was determined that tabu search (TS) was the most effective approach for this optimization problem. The TS algorithm employed is summarized in **Figure 1**. A detailed description of the TS meta-heuristic can be found in [12].

The operation of our tabu search approach can be characterized by the following components: starting configuration; moves; evaluation type and cost function.

4.1. Starting Configuration

The starting configuration can impact on the final configuration achieved by the TS. Having investigated a number of starting configurations (*i.e.*, all transmitters inactive, all transmitters active, random transmitters active and Halton configuration - approximately random uniformly distributed) it has been shown that whilst the

```
Generate starting configuration.
Evaluate cost of starting configuration.
Set best_cost_so_far = 0.
Initialise memory structures.
FOR i = 0 to max_iteratations DO
    Evaluate all possible moves.
    Sort moves on cost (prioritization).
    Accept first move where move is non-tabu or is tabu but meets aspiration criteria.
    Update memory structures.
    IF cost of configuration after move improves upon best_cost_so_far
      THEN
        Set best_configuration = current configuration.
        Set best_cost_so_far = cost of current configuration.
      END IF
END FOR
```

Figure 1. Generic tabu search algorithm

effectiveness of each starting configuration is dependent on the problem scenario and other parameter settings, starting with all transmitters inactive leads to the best solutions in general.

4.2. Moves

A range of different moves are employed by the TS. At each iteration of the TS, the impact of each of the available moves is evaluated by applying the move to each candidate antenna in order to determine the best possible move at that instance. The quality of each move is determined by the cost function. A range of moves have been implemented from which a subset of moves can be selected for evaluation:

- Activate an inactive transmitter *i.e.* make operational.
- Deactivate an active transmitter *i.e.* shut down.
- Swap transmitters:
- Deactivate an active transmitter and activate a randomly selected inactive transmitter .
- Activate an inactive transmitter and deactivate a randomly selected active transmitter .
- Determine the best azimuth for a transmitter - the azimuth for a given transmitter is varied (controlled by *azimuth_increment*) such that all available azimuth configurations in the sector are evaluated. The configuration with the best cost can then be determined.
- Determine the best tilt for a transmitter - the tilt for a given transmitter is varied (controlled by *tilt_increment*) such that all available tilt configurations in the range *tilt_max* to *tilt_min* are are evaluated. The configuration with the best cost can then be determined.

4.3. Evaluation Type

When evaluating moves, cost functions are employed in conjunction with an evaluation type. The evaluation type defines the evaluation heuristic used to determine service (*i.e.* uplink or downlink evaluation heuristic) and any constraints on the feedback mechanism employed to determine total load. In its least constrained form the iterative feedback mechanism repeats until the variation in the load is less than a predefined threshold. Iterating to convergence may require much iteration. This is time consuming and additional iterations achieve decreasing returns. As a result, in order to achieve an acceptable runtime for the TS (which need to perform large numbers of evaluations) the number of feedback iterations is constrained when employed for evaluating moves, only running to convergence for the final TS solution.

4.4. Cost Function

TS requires that a cost is associated with problem configurations such that an optimal or near optimal configuration can be sought. A weighted cost function is employed to enable the following objectives to be considered:

1) Meet the constraint on the number of transmitters.
2) Maximise coverage.
3) Favour configurations with lower total loads.

The tabu search seeks to minimize the total cost of a configuration, defined as:

$$total\_cost = (covg\_cost * w_c) + (actv\_cost * w_a) + (ld\_cost * w_l) \quad (6)$$

where w_c, w_a and w_l are weightings for *coverage cost*, *active cost* and *load cost* respectively.

Coverage cost is defined as

$$covg\_cost = 100 - coverage \quad (7)$$

where *coverage* is the percentage of *stp* that are covered in the downlink or uplink direction.

Active cost is defined as

$$actv\_cost = trans\_thrs - active\_trans \quad (8)$$

where *trans_thrs* is the desired number of active transmitters and *active_trans* is the number of active transmitters.

Load cost is defined as

$$ld\_cost = \sum \eta_{DL} \quad (9)$$

for all active transmitters in the downlink direction and

$$ld\_cost = \sum \eta_{UL} \quad (10)$$

for all active transmitters in the uplink direction.

It should be noted that as some objectives are competing (*e.g.* coverage and total load) it may not be possible to determine the configuration which exhibits the optimal trade-off between objectives. This would require a more complex (and time consuming) multi-objective approach.

5. Experimentation

The purpose of experimentation is to compare the performance of network configurations generated using uplink and downlink evaluation heuristics. Performing optimization for both link directions is time consuming. Consequently, it would be useful if we could identify an optimization configuration that provides a good trade-off between optimizing for uplink and for downlink, *i.e.*, a single approach that produces network configurations that perform well in both link directions. Whilst this trade-off may not be acceptable when producing final configurations, it could be beneficial in preliminary stages of network planning where some accuracy can be traded for the decreased evaluation time associated with optimizing for a single link direction.

5.1. Test Problems

All experiments consider a 3km x 3km transmission region containing 36 directional candidate antennae located at 12 uniformly distributed sites. Eight different problem scenarios have been considered as summarized in **Table 4**. Each scenario consists of a number of uniformly distributed *stp* with defined service requirements. Different scenarios have been generated by varying the number of *stp* considered and the distribution of services over these *stp*. Scenarios 5a, 5b and 5c have the same number of *stp* and number of *stp* with each service requirement, but a different distribution of these services over the *stp*. Signal attenuation is defined by the Hata path loss model.

5.2. TS Configuration

The tabu search was constrained to run for a maximum of 400 iterations and terminate after 50 iterations in which there is no improving move.

For each scenario and evaluation heuristic, two sets of moves are employed:

1) Activate/deactivate transmitter and swap transmitter activity (AS).

2) Activate/deactivate transmitter, swap transmitter activity, best tilt and best azimuth (ASBTBA)[1].

These sets of moves were selected in order to investigate the impact of tuning the configuration of the antennae.

6. Results

In this section we present the results of optimization for each problem scenario. For each problem scenario, a number of *problem instances* are considered, each with different constraints on the maximum number of antennae allowed. Four *optimization approaches* are considered:

1) DL optimisation heuristics with AS
2) DL optimisation heuristics with ASBTBA
3) UL optimisation heuristics with AS
4) UL optimisation heuristic with ASBTBA

On completion of the TS the resulting configuration is evaluated for the opposite link direction, *i.e.*:

•DL optimize and evaluate configuration for DL and UL percentage coverage/service, and load.

•UL optimize and evaluate configuration for DL and UL percentage coverage/service, and load.

This enables us to determine how well configurations optimized in one link direction perform with respect to the opposite link direction. Further analysis is undertaken to determine:

1) *Coverage Difference* ('Covg Diff' column in the tables) - the difference between uplink and downlink coverage for each instance of a problem scenario. This gives an indication of how optimizing for one link direction impacts on the other.

2) *Maximum DL Coverage Difference* ('Max DL Covg Diff' column) - for each instance of a problem scenario the *maximum percentage DL coverage* ('Max % DL Covg' column) for all optimization approaches is identified *i.e*. the maximum percentage DL coverage obtained from the DL or UL optimized AS or ASBTBA method. From this, the *Maximum DL Coverage Difference* is determined (by subtracting the coverage obtained for a problem instance from the maximum percentage DL coverage value), *i.e.* this indicates how well an optimization approach performs with respect to the best result. Consequently, this value gives an indication of which optimization approach performs best for each problem instance, and over all problem instances (based on the mean value).

3) Maximum UL Coverage Difference ('Max UL Covg Diff' column) - as Maximum DL Coverage Difference, but in the uplink direction.

6.1. Sample Results

Due to the volume of results generated from experimentation, only a subset of results is presented here[2]. For Problem 1, the results of all optimization approaches *i.e.* AS and ASBTBA are included (see **Tables A1 to A4** in Appendix A). For other problems, the results for optimization approach ASBTBA are presented only (see **Tables**

Table 4. Problem scenarios.

		No. stp assigned per service type					
Scenario	No. stp	Pilot	12.2 kbps	64kbps	144 kbps	384 kbps	Total Capacity Req (kbps)
1	441	100	220	44	44	23	20,668
2	441	147	0	294	0	0	18,816
3	441	392	0	0	49	0	18,816
4	961	630	220	44	44	23	20,668
5a, 5b, 5c	961	299	440	88	88	46	41,336
6	3721	1116	1675	372	372	186	169,235

[1]For best tilt and best azimuth moves, an increment of 1 degree is applied.

[2]A complete set of results can be found in Appendix B at: www.cs.cf.ac.uk/bounds/documentation.htm

Table 5. Analysis summary.

Link Direction/ Optimisation Method	Highest Mean DL Covg	Highest Mean UL Covg	Lowest Mean Covg Difference	Lowest Mean Max DL Covg Differnece	Lowest Mean Max UL Covg Difference	Lowest Combined Mean Covg Difference
DL AS	1		3	1		
DL ASBTBA	2, 3, 4, 5a, 5b, 5c, 6			2, 3, 4, 5a, 5b, 5c, 6		
UL AS		3		3		2
UL ASBTBA		1,2,3,4,5a, 5b, 5c, 6	1, 2, 4, 5a, 5b, 5c, 6		1, 2, 3, 4, 5a, 5b, 5c, 6	1, 3, 4, 5a, 5b, 5c, 6

A5 to A18 in Appendix A) as these performs best in general (see Section 6.2).

6.2. Analysis of Results and Conclusions

In order to compare the effectiveness of the different optimization approaches, we examine for each scenario which approach gives the best performance with respect to a number of metrics:

1) highest mean DL % coverage ('Highest Mean DL Covg' column);

2) highest mean UL % coverage ('Highest Mean UL Covg' column);

3) lowest mean coverage difference ('Lowest Mean Covg Difference' column), *i.e.* for each scenario which method gives the lowest *Coverage Difference* value;

4) lowest mean maximum DL coverage difference (Lowest Mean Max DL Covg Difference' column) *i.e.* for each scenario which method gives the lowest mean *Maximum DL Coverage Difference* value;

5) lowest mean maximum UL coverage difference (Lowest Mean Max UL Covg Difference' column), *i.e.* as above but defined for UL, and

6) lowest combined (*i.e.*, DL and UL) mean coverage difference ('Lowest Combined Mean Covg Difference' column) *i.e.* for each scenario which method gives the lowest value when adding the maximum DL and UL coverage difference means.

The results of this summary analysis can be seen in **Table 5** which indicates the optimization method/ scenario combination that gives the best result for each of the above six metrics. As expected, the results show that including antenna configuration moves during optimization leads to increased coverage[3].The results show that the DL ASBTBA optimization approach generally leads to the best downlink coverage and therefore the best *i.e.* lowest mean maximum DL coverage difference. Similarly the UL ASBTBA approach is consistently the best in terms of uplink.

Furthermore UL ASBTBA leads to the best (lowest) combined mean coverage difference *i.e.* for scenarios 1,3,4,5a,5b,5c and 6. This indicates that although optimization using the UL ASBTBA approach does not lead to the best levels of downlink coverage (though it is competitive in many places as illustrated by low mean maximum DL coverage difference values) it does result in the best overall combined mean coverage difference indicating that it performs better in terms of DL coverage than DL optimization does in terms of UL coverage. As a result, where time for planning a network is limited, the experimental results presented here suggest that a compromise in many cases is to optimize for uplink only rather than optimizing in both the uplink and downlink directions.

[3]This is also confirmed by Amaldi *et al* in [2] who have also shown that it is preferable to simultaneously optimize antenna location and configuration than to do so separately.

7. Acknowledgements

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8. References

[1] S. Hurley, "Planning Effective Cellular Mobile Radio Networks," *IEEE Transactions on Vehicular Technology*, Cardiff, Vol. 51, No. 2, March 2002, pp 243-253.

[2] E. Amaldi, A. Capone, F. Malucelli and F. Signori, "Optimization Models and Algorithms for Downlink UMTS Radio Planning," *Proceedings of Wireless Communications and Networking*, Milan, Vol. 2, March 2003, pp. 827-831.

[3] E. Amaldi, A. Capone, F. Malucelli and F. Signori, "A Mathematical Programming Approach for W-CDMA Radio Planning with Uplink and Downlink Constraints," *Proceedings of the Vehicular Technology Conference*, 2003. Vol. 2, October 2003, pp. 806-810.

[4] E. Amaldi, A. Capone, F. Malucelli and F. Signori, "Radio Planning and Optimization of W-CDMA Systems," *Lecture Notes in Computer Science - Personal Wireless Communications*, Vol. 2775, 2003, pp. 437-447.

[5] E. Amaldi, A. Capone and F. Malucelli, "Radio Planning and Coverage Optimization of 3G Cellular Networks," *Wireless Networks,* Vol. 14, No. 4, August 2008, pp. 435-447.

[6] J. Zhang, J. Yang, M. E. Aydin, and J. Y. Wu, "Mathematical Modelling and Comparisons of Four Heuristic Optimization Algorithms for WCDMA Radio Network Planning," *Proceedings of the International Conference on Transparent Optical Networks*, 2006, Vol. 3, June 2006, pp. 253-257.

[7] J. Yang, M. E. Aydin, J. Zhang and C. Maple, "UMTS Base Station Location Planning: a Mathematical Model and Heuristic Optimisation Algorithms,"*Communications,* Vol. 1, No. 5, October 2007, pp. 1007-1014.

[8] S. B. Jamaa, Z. Altman, J. M. Picard and B. Fourestie, "Multi-objective Strategies for Automatic Cell Planning of UMTS Networks," *Proceedings of the Vehicular Technology Conference*, Vol. 4, May 2004, pp. 2420-2424.

[9] S. B. Jamaa, Z. Altman, J. M. Picard and B. Fourestie, "Combined Coverage and Capacity Optimisation for UMTS Networks," *Telecommunications Network Strategy and Planning Symposium*, Moulineaux June 2004, pp. 175-178.

[10] R. M. Whitaker, S. Allen and S. Hurley, "Efficient Offline Coverage and Load Evaluation for CDMA Network Modeling," *IEEE Transactions on Vehicular Technology*, Vol. 58, No. 7, August 2009, pp 3704-3712.

[11] L. Mendo and J. M. Hernando, "On Dimension Reduction for Next Generation Microcellular Networks," *IEEE Transactions of Communications*, Vol. 49, No. 2, 2001, pp. 243-248

[12] F. W. Glover and M. Laguna, "Tabu Search," Springer, 1997.

Appendix A

Table A1. Scenario 1 - DL Optimised (AS).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
15	12	97.7324	4.91592	93.424	6.92558	4.3084	97.9529	0.2205	97.5057	4.0817
13	12	96.5986	3.85497	92.9705	6.77027	3.6281	97.5057	0.9071	96.6916	3.7211
11	11	95.9184	4.51131	88.8889	5.65139	7.0295	96.6508	0.7324	93.424	4.5351
9	9	93.424	3.67729	80.7256	4.75283	12.6984	93.424	0	89.5692	8.8436
7	7	90.0227	3.61884	73.2426	4.2	16.7801	90.0227	0	85.6208	12.3782
Mean		94.73922		85.85032		8.8889		0.372		6.71194

Table A2. Scenario 1 - DL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
15	12	97.9529	5.45044	93.8776	6.90332	4.0753	97.9529	0	97.5057	3.6281
13	12	97.5057	5.54612	90.7029	5.94145	6.8028	97.5057	0	96.6916	5.9887
11	11	95.2381	4.56179	89.5692	5.69875	5.6689	96.6508	1.4127	93.424	3.8548
9	9	92.7438	4.30398	85.7143	4.98792	7.0295	93.424	0.6802	89.5692	3.8549
7	7	90.0227	3.69683	79.8186	3.9371	10.2041	90.0227	0	85.6208	5.8022
Mean		94.69264		87.93652		6.75612		0.41858		4.62574

Table A3. Scenario 1 - UL Optimised (AS).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
15	11	97.2789	4.23953	97.5057	8.27713	0.2268	97.9529	0.674	97.5057	0
13	10	95.9184	3.75661	95.6916	7.2764	0.2268	97.5057	1.5873	96.6916	1
11	11	94.7846	3.8032	93.424	6.22613	1.3606	96.6508	1.8662	93.424	0
9	9	91.61	3.14089	89.5692	5.12837	2.0408	93.424	1.814	89.5692	0
7	7	87.9819	2.88475	81.1791	4.09059	6.8028	90.0227	2.0408	85.6208	4.4417
Mean		93.51476		91.47392		2.13156		1.59646		1.08834

Table A4. Scenario 1 - UL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % ULCovg	Max UL Covg Diff
15	12	97.5057	4.39257	97.5075	8.29146	0.0018	97.9529	0.4472	97.5075	0
13	11	96.3719	4.33431	96.6916	7.24909	0.3197	97.5057	1.1338	96.6916	0
11	9	96.6508	3.28007	93.1973	6.17624	3.4535	96.6508	0	93.424	0.2267
9	9	91.1565	2.98996	89.1156	5.4	2.0409	93.424	2.2675	89.5692	0.4536
7	7	89.1156	3.37209	85.2608	4.08703	3.8548	90.0227	0.9071	85.6208	0.36
Mean		94.1601		92.35456		1.93414		0.95112		0.20806

Table A5. Scenario 2 - DL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
15	12	92.0635	7.76091	91.3832	8.12563	0.6803	92.0635	0	93.424	2.0408
13	12	89.7959	6.94523	86.6213	7.26294	3.1746	89.7959	0	89.3424	2.7211
11	11	85.7143	6.02062	82.7664	6.6	2.9479	85.7143	0	83.22	0.4536
9	9	79.3651	4.92076	75.737	5.10716	3.6281	79.3651	0	77.3243	1.5873
7	7	71.4286	3.97083	68.4807	4.1063	2.9479	71.4286	0	68.9342	0.4535
Mean		83.67348		80.99772		2.67576		0		1.45126

Table A6. Scenario 2 - UL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
15	12	90.4762	6.80249	93.424	8.68051	2.9478	92.0635	1.5873	93.424	0
13	12	87.9819	5.60654	89.3424	7.8	1.3605	89.7959	1.814	89.3424	0
11	11	83.22	5.42435	83.22	6.48371	0	85.7143	2.4943	83.22	0
9	9	78.2313	4.23473	77.3243	5.3544	0.907	79.3651	1.1338	77.3243	0
7	7	70.9751	3.65601	68.9342	4.16268	2.0409	71.4286	0.4535	68.9342	0
Mean		82.1769		82.44898		1.45124		1.49658		0

Table A7. Scenario 3 - DL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
15	12	98.8662	2.15203	99.5465	7.59356	0.6803	99.5465	0.6803	100	0.4535
13	12	99.093	2.55291	99.093	5.97961	0	99.093	0	99.7732	0.6802
11	10	98.6395	2.67339	98.1859	5.05613	0.4536	98.6395	0	99.093	0.9071
9	9	97.9592	3.08148	97.2789	4.58512	0.6803	97.9592	0	97.9592	0.6803
7	6	96.3719	2.44903	95.9184	3.82552	0.4535	96.5986	0.2267	96.5986	0.6802
Mean		98.18596		98.00454		0.45354		0.1814		0.68026

Table A8. Scenario 3 - UL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
15	12	99.3197	2.45275	100	6.94763	0.6803	99.5465	0.2268	100	0
13	11	99.093	2.50739	99.7732	6.52997	0.6802	99.093	0	99.7732	0
11	10	98.1859	2.21099	99.093	5.88246	0.9071	98.6395	0.4536	99.093	0
9	9	97.5057	2.25701	97.9592	5.01653	0.4535	97.9592	0.4535	97.9592	0
7	7	96.5986	2.44812	96.5986	4.02627	0	96.5986	0	96.5986	0
Mean		98.14058		98.6848		0.54422		0.22678		0

Table A9. Scenario 4 - DL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
15	12	98.231	3.48392	95.0052	5.71615	3.2258	98.3351	0.1041	98.231	3.2258
13	12	98.4391	4.22513	96.0458	5.90235	2.3933	98.4391	0	97.9188	1.873
11	10	97.8148	4.23715	92.82	4.91646	4.9948	97.8148	0	96.7742	3.9542
9	9	97.0864	4.48578	92.5078	5.04474	4.5786	97.0864	0	95.3174	2.8096
7	7	95.3174	3.85111	89.4901	4.2	5.8273	95.3174	0	93.3403	3.8502
Mean		97.37774		93.17378		4.20396		0.02082		3.14256

Table A10. Scenario 4 - UL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
15	11	98.0229	3.93876	98.231	7.83294	0.2081	98.3351	0.3122	98.231	0
13	11	98.0229	4.08886	97.9188	7.36299	0.1041	98.4391	0.4162	97.9188	0
11	10	97.1904	3.7737	96.7742	6.17889	0.4162	97.8148	0.6244	96.7742	0
9	9	95.6296	3.40389	95.1093	5.27193	0.5203	97.0864	1.4568	95.3174	0.2081
7	7	94.589	3.03997	93.3403	4.16951	1.2487	95.3174	0.7284	93.3403	0
Mean		96.69096		96.27472		0.49948		0.7076		0.04162

Table A11. Scenario 5a - DL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
30	12	95.7336	8.8114	92.2997	13.69	3.4339	95.7736	0.04	94.7971	2.4974
28	12	95.0052	8.15436	90.5307	12.7677	4.4745	95.0052	0	94.3809	3.8502
26	12	95.1093	8.94051	88.9698	12.7132	6.1395	95.1093	0	93.9646	4.9948
24	12	94.7971	9.22445	87.513	10.9784	7.2841	94.7971	0	92.2591	4.7461
22	12	93.9646	8.67947	84.2872	11.1338	9.6774	93.9646	0	91.155	6.8678
Mean		94.92196		88.72008		6.20188		0.008		4.59126

Table A12. Scenario 5a - UL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
30	12	94.2768	14.8372	94.7971	16.3076	0.5203	95.7736	1.4968	94.7971	0
28	11	93.9646	7.50289	94.3809	15.5006	0.4163	95.0052	1.0406	94.3809	0
26	11	93.8606	7.97812	93.9646	14.5485	0.104	95.1093	1.2487	93.9646	0
24	11	92.4037	12.1858	91.8835	13.4864	0.5202	94.7971	2.3934	92.2591	0.3756
22	11	92.6119	8.14166	91.155	12.9164	1.4569	93.9646	1.3527	91.155	0
Mean		93.42352		93.23622		0.60354		1.50644		0.07512

Table A13. Scenario 5b - DL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
30	12	94.3809	6.92736	93.1322	15.2262	1.2487	94.693	0.3121	94.7971	1.6649
28	12	95.2133	8.13099	93.7565	14.1049	1.4568	95.2133	0	94.1727	0.4162
26	12	94.7971	8.19764	91.051	15.6	3.7461	94.7971	0	94.849	3.798
24	12	94.1727	7.94107	92.4037	13.511	1.769	94.1727	0	92.7159	0.3122
22	12	93.7565	8.33987	88.5536	13.2	5.2029	93.7565	0	90.9469	2.3933
Mean		94.46410		91.77940		2.68470		0.06242		1.71692

Table A14. Scenario 5b - UL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
30	12	93.7565	14.4344	94.589	15.9992	0.8325	94.693	0.9365	94.7971	0.2081
28	12	93.6524	7.0646	94.1727	16.0077	0.5203	95.2133	1.5609	94.1727	0
26	12	93.8606	6.80798	94.849	14.5496	0.9884	94.7971	0.9365	94.849	0
24	12	93.1322	7.31611	92.7159	13.1161	0.4163	94.1727	1.0405	92.7159	0
22	11	91.3632	11.3738	90.9469	12.3443	0.4163	93.7565	2.3933	90.9469	0
Mean		93.15298		93.45470		0.63476		1.37354		0.04162

Table A15. Scenario 5c - DL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
30	12	95.2133	8.6136	91.155	18	4.0583	95.2133	0	94.7971	3.6421
28	12	94.7971	8.33628	92.5078	13.8027	2.2893	94.7971	0	94.9011	2.3933
26	12	94.4849	8.44079	91.155	12.5475	3.3299	94.4849	0	93.6524	2.4974
24	12	94.693	9.255303	89.8023	11.7329	4.8907	94.693	0	92.4037	2.6014
22	12	94.0687	9.59018	87.0968	10.4895	6.9719	94.0687	0	92.6119	5.5151
Mean		94.65140		90.34338		4.30802		0		3.32986

Table A16. Scenario 5c - UL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
30	12	94.693	8.98932	94.7971	16.1597	0.1041	95.2133	0.5203	94.7971	0
28	12	94.589	8.86264	94.9011	15.5587	0.3121	94.7971	0.2081	94.9011	0
26	11	93.5484	8.20557	93.6524	14.5616	0.104	94.4849	0.9365	93.6524	0
24	11	93.2362	8.83864	92.0916	12.937	1.1446	94.693	1.4568	92.4037	0.3121
22	11	92.924	7.51445	92.6119	12.8082	0.3121	94.0687	1.1447	92.6119	0
Mean		93.79812		93.61082		0.39538		0.85328		0.06242

Table A17. Scenario 6 - DL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
30	12	76.5117	16.5578	53.5609	14.0817	22.9508	76.5117	0	60.602	7.0411
28	12	75.6248	15.7692	52.3246	13.2735	23.3002	75.6248	0	58.8283	6.5037
26	12	75.6517	14.9694	53.9371	13.9292	21.7146	75.6517	0	57.4308	3.4937
24	12	78.8723	13.9065	51.5453	12.5168	27.327	78.8723	0	57.4577	5.9124
22	12	73.4211	12.9731	50.1478	11.526	23.2733	73.4211	0	54.9583	4.8105
Mean		76.01632		52.30314		23.71318		0		5.55228

Table A18. Scenario 6 - UL Optimised (ASBTBA).

Num Tx	Num Sites	DL % Covg	DL Load	UL % Covg	UL Load	Covg Diff	Max % DL Covg	Max DL Covg Diff	Max % UL Covg	Max UL Covg Diff
30	12	74.308	15.7713	60.602	17.7095	13.706	76.5117	2.2037	60.602	0
28	12	73.3405	14.5942	58.8283	16.0287	14.5122	75.6248	2.2843	58.8283	0
26	12	71.6743	14.0077	57.4308	15.2955	14.2435	75.6517	3.9774	57.4308	0
24	12	71.5937	13.1524	57.4577	14.4	14.136	78.8723	7.2786	57.4577	0
22	12	69.9543	12.3729	54.9583	13.0276	14.996	73.4211	3.4668	54.9583	0
Mean		72.17416		57.85542		14.31874		3.84216		0