7 Conclusions and Future Work

7.1 Discussion and conclusions

The objective of this research was to investigate the relationship between field strength and the actual levels of SAR in the human body encountered in close proximity to high gain high power HF broadcast antennas. In order to assess the human exposure against ICNIRP guidelines, it has led to the development of a series of assessments of modelling techniques, mechanical configuration and environment of a transmission site. Due to the complex nature of this EM problem, each chapter of this thesis covers the key developments of particular sub-projects in different areas. The findings of each area correspond to the ICNIRP occupational and public exposure guidelines; they formed the reference parameters in the primary assessments which could apply to a range of similar EM scenarios. The chapters of this thesis do not necessarily follow a chronological order. Various potential influential aspects of assessing the human exposure levels were addressed during continuous problem solving processes, including several issues have not been covered in other research before.

There are three areas that have been covered in this thesis, firstly relating whole body SAR to incident plane-wave fields in correlation with ICNIRP basic restriction and reference levels. Second, near-zone incident fields characteristic were assessed by simulations and analyses the results, where some exposure assessment protocols for ICNIRP compliance was derived. Thirdly real-time field measurements were carried out to consolidate the findings from the theoretical modelling analysis.

The first part of the study predicted the external electric field values corresponding to restrictions on whole body SAR. Numerical human phantoms were the primary investigation objects. Homogenous human phantoms were built in the primitive study. Commercial heterogeneous human phantoms were used to calculate the induced whole body SAR in this thesis. Studies comprise of phantom types, phantom complexity and modelling techniques and ground coupling. Their effects were successfully addressed. The findings of phantom variations gave an overview of the human gender and relative physical difference caused by different energy absorption when exposed in a same

EMF. The process of exploring suitable modelling techniques helped to achieve a protocol to simplify heterogeneous human phantom models. The protocol includes adequate numbers of phantom tissue type and voxel resolutions for studies in these projects as well as other similar EM problems. Conventional studies would assume that the human body is standing on a perfect electric conducting ground, either isolated with a rubber 'shoes' layer or perfectly grounded. However, the realistic ground coupling simulation results in chapter 3 addressed that the ground conditions caused SAR variation in human body, and would have significant impact on the required incident E-field level to exceed the ICNIRP limits.

The Skelton C (Cumbria, UK) curtain array antenna 766 was chosen for the second part of this thesis. Initial antenna modelling found that the near zone fields of the high power high gain HF broadcasting antenna was complicated by the antenna support structures and ground interactions. This lead to a full investigation of the transmitter site comprised of antenna complexity, local terrain topography, array infrastructure, input power and ground dielectric conditions. The comparisons of the simulation results successfully differentiate the influential parts and their effects on the antenna near-field zone. The results in chapter 4 show that despite the fact that Skelton C curtain array antenna 766 consists of an array of horizontal dipole elements, there are strong vertical E-field components present in the very close region near the array. These were the joint effects of scatterers and ground reflections. The effects of various ground conditions and array infrastructure on the antenna near-field distribution have shown that the horizontal components are also very high at human shoulder height. Considering that standing humans are more sensitive to vertical E-field component, if the predominant field is the vertically polarized E-field, the ankle region would be the restrictive quantity. The human body coupled better with the horizontally polarized field component when standing with arms stretched out. Likewise, if the horizontal polarized field component is the predominant field, the localized SAR in the wrist and ankle need to be considered as the restrictive quantity. However, the 'arms out' human is a worse case. The findings in Chapter 4 show that the E-field in front of the array was complex and had a non-uniform distribution. The predominant field component varies from area to area. The measured results in Chapter 6 consolidate the conclusion. Therefore, the restrictive quantity would depend on the EMF where the human was standing. This gave the confidence to start an in depth investigation on various factors and their influences on the EMF field distribution. A series of useful parameters were successfully addressed for a particular part of the HF transmitting site. It was found that ground slope would cause the distortion and asymmetry of the near-field of the antenna. Because of this, it was found that Ez increases with the ground slope angle increase when Ey increases at the higher ground whilst decreasing at the lower end of the ground. Array infrastructures also changed the Ey distribution patterns and increased the level of the E-field as well as enlarging the higher field region. Ez was less affected by the metal structure above the ground and it reduced the area of higher EMF values. These results gave good guidance when applying the findings to other similar high power HF antenna. They also assist the EMF mapping for human exposure hazard assessments.

The third part of the thesis presents the development of field strength measurement system for the Skelton C curtain array antenna designed to validate simulated E-field distributions. Ankle currents were measured on two people. The phantoms used in Chapter 3 were specially chosen to bear similar physical resemblance to the subjects (the author - Billie and her supervisor - Duke). The vertical and horizontal components of the field were measured separately at a preselected distance in front of the array. Comparison of numerically simulated results and measurements were made on shape and pattern rather than actual magnitude levels. Although the measurements do not totally agree with the predicted field but the general trends were consistent with the findings in chapter 4, including effects on the near-field caused by local terrain topography, ground slope as well as the array infrastructures. If we compare the simulated graph obtained using a ground of 2 degrees with that obtained through measurement, their general shapes are in good agreement. This could be attributed to factors that were not accounted for in the simulations, or due to dimensional errors on the test antenna which deviate from those specified in the drawings. Other factors include: the exact profile of the ground terrain, infrastructure associated with the transmitter, and heavy precipitation in the air on the day of the test which also had the effect of making the ground very wet and so changing its electrical conductivity. The ankle current measurement is consistent with the pattern of the field measured using our dipole. This has validated this new measurement set-up and procedure. The measurements results in Chapter 6 prove that the local terrain and array infrastructure have a **significant impact** on the distribution of near-field antenna. These findings further consolidate the findings presented in Chapter 4. This thesis also identified the higher and lower E-field strength regions in front of array in relation to influential factors. Moreover, there are several attempts to model a realistic human phantom in the vicinity of the near zone antenna fields for SAR determination modelling. These attempts include novel hybrid numerical methods.

In Summary, the work of this thesis provides some valuable insights into the process of assessing the human exposure in the near-field of a high power HF antenna against ICNIRP guidelines. Commercial anatomical human phantoms (Virtual Family) were successfully validated and used in the estimation of SAR induced by plane-wave irradiation. The effects of gender, human physical variance, ground conditions and several other modelling techniques were studied and addressed successfully for future works. Electric field strength values required to produce the ICNIRP basic restrictions were derived in various exposure conditions. The basic principles of assessing the near zone EMF characteristics of the HF transmitting site were established. The influential aspects and their effects were successfully addressed. A final field measurements system was developed and the comparisons of calculated and measured results provide useful validation information. Overall, the objectives of this study have been achieved. The findings of this thesis provides a general guide to both workers and the public when assessing the human exposure hazard in the near-field region of high power HF transmitting sites.

The research presented in this thesis has provided a comprehensive academic overview on the assessment of emissions from HF transmission sites in relationship with human exposure against ICNIRP guidelines. The works listed below will be helpful to extend the study in helping broadcasters and the public to assess compliance with the ICNIRP exposure guidelines. Some of the results have been published in various peer reviewed conference papers. It is anticipated that some of the research present here will be submitted and published in leading academic journals.

7.2 Limitations

Aspects of the work have several limitations or constraints in simulation, statistical analysis and measurements. This thesis considered 1W plane-wave irradiation incidence in humans. All the phantoms were irradiated from chest to back (Antero

Posterior AP) direction, which is the shortest body length. Realistically, humans are active and could be standing in any direction. The effects of incoming electromagnetic waves in other directions on the SAR in human bodies were not included in this thesis. At the HF frequency band, human phantom simulations in FDTD methods required a very long time to reach a steady state. Most of the models were run in eight core computer servers with 64 GB of RAM and two NVIDIA C1060 Tesla graphics processing unit (GPU). To calculate the full scale antenna model required a lot of RAM. The hybrid (Huygens Box and FDTD) numerical method was tested. The aim of using this novel approach was to reduce the requirements of time, computer hardware and resources for SAR simulation and calculation. Unfortunately, the methods could not provide satisfactory performance due to the constraints of the software. The whole-body SAR simulations were still running at a very slow pace. Each plane-wave human irradiation simulation needed an average of 20-24 hours. CST microwave studio could not couple with the full scale antenna model with human phantoms implemented for a whole-body SAR calculation. Localised SAR in the ankle and wrist regions was not investigated at this stage. The comparisons between predicted field and measured field could not be fully matched, indicating that there are more potential influential factors have not been addressed. There are also measurement uncertainties such as equipment, environmental interference (weather, ground conditions), and location topography. These could add difficulties in comparison with theoretically modelled results.

7.3 Future work

Further work could be conducted in human phantom and antenna modelling analysis as well as for the SAR calculation and field measurement. The horizontal field component can be quite high in some area closes to the antenna, therefore localized SAR in wrist region is necessary to consider and be further investigated. The unsatisfactory performance of the numerical hybrid method can be ameliorated with improvements to the numerical simulation software. The same problem occurred when it was unable to complete to SAR calculation when placing the human phantom in the full scale transmitting site model. If successful, this should give a valuable insight into the behaviours of intensive non-uniform near-field EMF and its effects on humans. This would be a direct human exposure level in compliance to ICNIRP guidelines. The latest version of software might be able to solve the problem and may be more suitable for the future studies. The lossy ground was only considered to be an average ground condition ($\varepsilon_r = 13$ and $\sigma = 0.005$ S/m) in both human phantom plane-wave illumination and near-field characteristic modelling as a generalization standard. The measurements did not match the calculated field well. The difference of theoretical prediction and practical measurements suggest that there are other aspects and their effects on the EMF distribution can be investigated further, such as the infrastructure and feeders of the array. In addition to the antenna's mechanical complexity influence, the actual Skelton C curtain array antenna 766 is built above a field of grass. The field measurements were conducted in heavy rain and strong wind. Different ground condition models could be carried out in the future to eliminate some of the measurement uncertainties. These should give additional useful information when applying the findings to similar EM problems. If time and resources permitted, other HF transmitting sites, additional measurements and modelling would provide more information to verify the findings of this study.