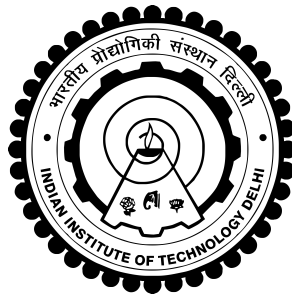


**ANALYSIS OF ENERGY EFFICIENCY AND QOS IN  
HETEROGENEOUS CLOUD RADIO ACCESS  
NETWORK**

**RAMAKRISHNAN S**



**BHARTI SCHOOL OF TELECOMMUNICATION  
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INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**AUGUST 2019**

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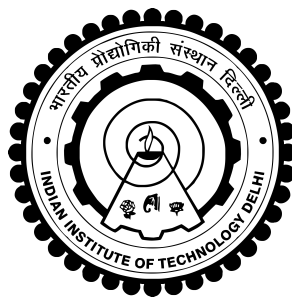
by

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Submitted

in fulfilment of the requirements of the degree of  
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to the



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# Certificate

This is to certify that the thesis titled **Analysis of Energy Efficiency and QoS in Heterogeneous Cloud Radio Access Network**, submitted by **Ramakrishnan S**, to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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**Ramakrishnan S**

# Abstract

To meet the capacity requirements for tremendous growth in mobile data traffic, Mobile Network Operators (MNOs) need to add more radio nodes and spectrum layers. This increases power consumption and therefore requires energy efficient solutions like deployment of Cloud based Radio Access network (RAN) and spectrally-efficient and power-efficient radio units like Large-Scale Antenna Systems (LSAS). Further, the spectrum layers vary in QoS, utilization and usage charges. To save operational costs, the MNOs share their radio networks. The MNOs, therefore, need to consider spectrum availability, link utilization, link usage costs, traffic handling priorities and QoS for selecting the Donor link for traffic offload. In this thesis, the network evolution towards C-RAN is presented. Three aspects of C-RAN were researched *.viz.* (a) Energy Efficiency in heterogeneous C-RAN, (b) Dynamic traffic steering in a shared multi-MNO C-RAN and (c) low latency Multi-Connectivity support in heterogeneous C-RAN.

For the overall energy efficiency of C-RAN, four components of the Radio network are considered – the Cloud base station, the Radio site, the front-haul network and the cooling systems. The Radio BBU processing which is moved to the cloud is quantified using a power model. For the scenario of when C-RAN is used with LSAS radio units with large antenna configurations, an appropriate base station architecture split is considered. The simulations were performed using a combination of simulators *viz.* NS3 (for LTE radio network simulation) and CloudSim Plus (for Cloud based base station simulation) in a phased manner. Further, the effect of base station’s scheduling algorithm *viz.* Proportionate-Fair or Round-Robin, on the computational complexity of the various base station sub-components is studied. Through the simulations, it is observed that the computational complexity was relatively higher for RR scheduling (compared to PF scheduling). But the variations of energy efficiency metric were similar for both the scheduling schemes for different base station configurations. Further, the energy efficiency of different variants of LSAS were compared

considering Macro2TR as reference.

Next, the traffic steering problem was analyzed for scenario of multi-MNO shared network with multiple donor links. Two different queuing models were evaluated to represent the heterogeneous C-RAN system for traffic offload scenario (a) network of queues with recursive offload and (b) traffic steering using MADM technique. Based on evaluation, the MADM technique based traffic steering is selected for further analysis due to limitations observed in the “recursive offload” method. For the MADM technique based traffic steering, a set of two hybrid MADM techniques are considered *viz.* (a) AHP-GRA and (b) Entropy-RoV techniques. The techniques were validated through a set of scenarios using different combinations of traffic load, usage cost and IP packet scheduling priority in the contending Donor links. The simulation is performed using MATLAB SimEvents and the results are presented. In all the scenarios, AHP-GRA as well as Entropy-RoV techniques offered benefits for overall Beneficiary link traffic with better average waiting time by aligning with the dynamism of the network. AHP method required pre-configuration of the network through pair-wise comparison to derive weights of criteria for selection. The Entropy-RoV method was able to align with dynamism of the network without any pre-configuration.

Next, for the support of low latency LTE-NR Multi-connectivity scenario (specifically for E-UTRAN-NR Dual Connectivity configuration), the characteristics of the inter BTS links was analysed. A heterogeneous C-RAN was simulated with NS3 network simulator with heterogeneous mix of 4G and 5G-NR base stations. Through simulations, throughput requirement of inter BTS mid-haul link and the end-to-end delay sensitivity due to inter BTS mid-haul link delay are analysed. Further, “Neighbour Association-aware Placement” (NAP) algorithm is proposed for placement of the vBBUs in the Cloud server to avoid the inter VM latency and thus maintain lower overall delay at PDCP layer. It is found that the NAP algorithm is beneficial for Cloud based heterogeneous RAN supporting EN-DC and with delay sensitive traffic by offering higher capacity and maintaining lower end-to-end delay.

# सार

मोबाइल डेटा ट्रैफिक में जबरदस्त वृद्धि के वजह से मोबाइल ऑपरेटर्स (MNO) को अधिक से अधिक स्पेक्ट्रम एवं रेडियो को स्थापित करने की आवश्यकता है। इससे बिजली की खपत बढ़ती है। इसलिए ऊर्जा कुशल समाधान जैसे क्लाउड रेडियो एक्सेस नेटवर्क (C-RAN) अतवा लार्ज स्केल ऐन्टेना प्रणाली (LSAS) की जरूरत है। स्पेक्ट्रम की परतें QoS, उपयोग और उपयोग के शुल्क से भिन्न हो सकती हैं। परिचालन के लागत की वजह से, MNO उनके रेडियो नेटवर्क को साझा करते हैं। इसलिए, MNO को स्पेक्ट्रम उपलब्धि, स्पेक्ट्रम का उपयोग और उसका प्रभार, ट्रैफिक की प्राथमिकता और QoS को मानते हुए डोनर लिंक को चुनने की जरूरत है। इस थीसिस में क्लाउड के प्रति नेटवर्क के विकास को प्रस्तुत किया गया है। C-RAN के तीन पहलुओं पे शोध किया गया है (1) विजातीय C-RAN की ऊर्जा दक्षता (2) बहु MNO में ट्रैफिक की गतिशील स्टीयरिंग और (3) विजातीय C-RAN में कम विलंबता वाले मल्टी-कनेक्टिविटी का समर्थन।

C-RAN के सम्पूर्ण ऊर्जा दक्षता के लिए चार अवयव माना गया है - क्लाउड बेस स्टेशन, रेडियो साइट, फ्रॉन्टहाउल नेटवर्क और शीतलन प्रणाली। रेडियो बेसबैंड की प्रसंस्करण जो क्लाउड में ले जाया गया है, उसे पावर मॉडल का उपयोग करके मात्रा निसदरित किया गया है। जहाँ C-RAN को LSAS के साथ उपयोग किया है, वहाँ उपयुक्त आर्किटेक्चर के विभाजन को माना गया है। इस अनुसंधान में NS3 अथवा CloudSim Plus सिम्युलेटर्स का कई चरणों में उपयोग किया है। बेस स्टेशन के शेड्यूलिंग अल्गोरिथम (प्रोपोरशनेट फेयर या राउंड रोबिन) का, बेस स्टेशन के विभिन्न उप घटकों के कम्प्यूटेशनल कम्प्लेक्सिटी पर प्रभाव का अध्ययन किया गया है। सिमुलेशन के माध्यम से यह देखा गया है की राउंड रोबिन शेड्यूलिंग का कम्प्यूटेशनल कम्प्लेक्सिटी प्रोपोरशनेट फेयर शेड्यूलिंग से अधिक है। लेकिन विभिन्न बेस स्टेशन कॉन्फिगरेशन के लिए और शेड्यूलिंग अल्गोरिथम के लिए ऊर्जा दक्षता मेट्रिक की भिन्नता सामान थी। इसके अलावा, LSAS के विभिन्न प्रकार की ऊर्जा दक्षता को Macro2TR के सन्दर्भ के रूप में माना गया है।

इसके बाद, कई डोनर लिंक के साथ बहु MNO साझा नेटवर्क के परिदृश्य के लिए ट्रैफिक स्टीयरिंग समस्या का विश्लेषण किया गया था। ट्रैफिक ऑफलोड परिदृश्य (1) रिकर्सिव



ऑफलोड के साथ कतारों का नेटवर्क और (2) MADM तकनीक का उपयोग करके ट्रैफिक स्टीयरिंग के लिए विषम C-RAN प्रणाली का प्रतिनिधित्व करने के लिए दो अलग-अलग कतारबद्ध मॉडलों का मूल्यांकन किया गया है। मूल्यांकन के आधार पर, "रिकर्सिव ऑफलोड" पद्धति में देखी गयी सीमाओं के कारण MADM तकनीक आधारित ट्रैफिक स्टीयरिंग को आगे की विश्लेषण के लिए चुना गया है। MADM तकनीक आधारित ट्रैफिक स्टीयरिंग के लिए दो हाइब्रिड MADM तकनीकों का एक सेट महत्वपूर्ण माना गया है (1) AHP-GRA और (2) entropy-RoV तकनीक। तकनीकों को विभिन्न प्रकार के परिदृश्यों के माध्यम से मान्य किया गया था, जो कि डोनर लिंक ट्रैफिक लोड, उपयोग लागत और पैकेट शेड्यूलिंग प्राथमिकता के विभिन्न संयोजनों का उपयोग कर रहे हैं। सिमुलेशन MATLAB SimEvents का उपयोग करके किया गया है और परिणाम प्रस्तुत किये गए हैं। सभी परिदृश्यों में, AHP-GRA और साथ ही Entropy-RoV तकनीकों ने नेटवर्क गतिशीलता के साथ सरेखित करके बेहतर औसत प्रतीक्षा समय के साथ समग्र बेनेफिशरी लिंक के ट्रैफिक के लिए लाभ की पेशकश की। AHP विधि के चयन के लिए मानदंड प्राप्त करने के लिए जोड़ी-वार तुलना के माध्यम से नेटवर्क के पूर्व-विन्यास की आवश्यकता होती है। Entropy-RoV विधि किसी भी पूर्व-कॉन्फिगरेशन के बिना नेटवर्क की गतिशीलता के साथ सरेखित करने में सक्षम थी।

इसके बाद, कम विलंबता LTE-NR मल्टी-कनेक्टिविटी परिदृश्य (विशेष रूप से E-UTRAN-NR ड्यूल कनेक्टिविटी कॉन्फिगरेशन) के समर्थन के लिए, अंतर बेस स्टेशन लिंक के विशेषताओं का विश्लेषण किया गया है। एक विषम C-RAN को NS3 नेटवर्क सिम्युलेटर के साथ 4G और 5G-NR बेस स्टेशनों के विषम मिश्रण के साथ जोड़ा गया है। सिमुलेशन के माध्यम से, अंतर बेस स्टेशन लिंक की थ्रूपुट की आवश्यकता और इस लिंक के देरी के कारण समग्र संवेदनशीलता का विश्लेषण किया गया है। इसके अलावा, "नेइबर अवेयर प्लेसमेंट" (NAP) अल्गोरिथम को vBBU के क्लाउड सर्वर में अन्तर VM लेटेंसी से बचने के लिए प्रस्तुत किया गया था और इस प्रकार PDCP लेयर पर कम समग्र विलम्ब बनाये रखा जाता है। यह पाया जाता है कि EN-DC का समर्थन करने और संवेदनशील ट्रैफिक के साथ उच्च क्षमता की पेशकश और कम समग्र विलम्ब को बनाये रखने में NAP अल्गोरिथम विषम C-RAN के लिए फायदेमंद है।

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# List of Abbreviations

<b>4G</b>	4 <sup>th</sup> Generation
<b>5G</b>	5 <sup>th</sup> Generation
<b>5G-NR</b>	5 <sup>th</sup> Generation-New Radio
<b>AHP</b>	Analytical Hierarchical Process
<b>BBU</b>	Base Band Unit
<b>BTS</b>	Base Transceiver System
<b>CI</b>	Consistency Index
<b>CN</b>	Compute Node
<b>CPRI</b>	Common Public Radio Interface
<b>CR</b>	Consistency Ratio
<b>CRR</b>	Computational Resource Requirement
<b>CRAC</b>	Computer Room Air Conditioner
<b>C-RAN</b>	Cloud based Radio Access Network
<b>CTMC</b>	Continuous Time Markov Chains
<b>DC</b>	Dual Connectivity
<b>EARTH</b>	Energy Aware Radio and neTwork tecHnologies
<b>eCPRI</b>	evolved Common Public Radio Interface
<b>EPC</b>	Evolved Packet Core
<b>eLFF</b>	ethernet based Low Latency Fronthaul
<b>EN-DC</b>	E-UTRAN New Radio Dual Connectivity
<b>EPC</b>	Evolved Packet Core
<b>FFT</b>	Fast Fourier Transform
<b>GFLOPS</b>	Giga FLoating-point Operations Per Second
<b>GOPS</b>	Giga Operations Per Second
<b>GRA</b>	Grey Relational Analysis
<b>GRC</b>	Grey Relational Coefficient

<b>IFFT</b>	Inverse Fast Fourier Transform
<b>LSAS</b>	Large Scale Antenna Systems
<b>LTE</b>	Long Term Evolution
<b>MAC</b>	Media Access Control
<b>MIMO</b>	Multiple Input Multiple Output
<b>MNO</b>	Mobile Network Operator
<b>MVNO</b>	Mobile Virtual Network Operator
<b>MU-MIMO</b>	Multi User Multiple Input Multiple Output
<b>NR</b>	New Radio
<b>OFDM</b>	Orthogonal Frequency Division Multiplexing
<b>OLT</b>	Optical Line Termination
<b>ONU</b>	Optical Network Unit
<b>PDCP</b>	Packet Data Control Protocol
<b>PON</b>	Passive Optical Network
<b>QBD</b>	Quasi Birth Death
<b>RAN</b>	Radio Access Network
<b>RN</b>	Relay Node
<b>RoV</b>	Range of Values
<b>RRC</b>	Radio Resource Control
<b>RRH</b>	Remote Radio Head
<b>RRU</b>	Remote Radio Unit
<b>SDN</b>	Software Defined Networking
<b>SISO</b>	Single Input Single Output
<b>TWDM</b>	Time and Wavelength Division Multiplexing
<b>vBBU</b>	virtual Base Band Unit
<b>VM</b>	Virtual Machine