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MASTER THESIS

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Improving Energy Efficiency in 5G Ultra-Dense Networks

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This Master Thesis is Prepared by Mosheer Jamal Da'as in part fulfillment of the degree requirements for the Joint Master in Electrical Engineering-Telecommunications, JMEE Program.

Declaration of Authorship

I, Mosheer DA'AS, declare that this thesis titled, "Improving Energy Efficiency in 5G Ultra-Dense Networks " and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at Birzeit University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at Birzeit University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
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“The best way to predict your future is to create it — Abraham Lincoln.”

“Life is like riding a bicycle. To keep your balance you must keep moving — Albert Einstein.”

Abstract

Next generation 5G networks specifications are being developed with high promised capabilities, the aim is to have higher user throughput, better energy and spectrum efficiency, less latency, and to serve the huge number of candidate users and Internet of Things (IoT). It is expected that 5G radio networks will strongly depend on using ultra-dense small cells beside the macro base stations. This topology will overcome problems of coverage-holes due to millimeter-wave signals, demanded user throughput and high number of attached users. This kind of ultra-dense networks (UDN) consisting of large number of macro and small cells will significantly increase network power requirements. A practical method to control energy consumption is by dynamically controlling power saving mode in radio network.

In this thesis, a cooperative energy management algorithm for 5G UDN model is developed, such that the overall energy consumption is reduced while maintaining network coverage and user demanded quality of service. The mobile network is modeled as a graph; this model allows using graph theory properties to build energy optimization algorithm. Graph connectivity is an important measure to guarantee continued radio coverage, design algorithm secures network connectivity and measures it through algebraic connectivity. This work introduces a novel power saving algorithm for such multi-layer, multi-band heterogeneous UDN using power off/on method. The algorithm is self maintained and works using centralized management database without additional complexity in network architecture.

The proposed algorithm achieves power saving up to 21% in daily peak time, and 60% in off-peak time coming from energy saved on macro and small cells, beside the connecting backbone links. To validate the effectiveness of the proposed algorithm, a random network model is developed using Matlab, and several experiments are simulated to test the robustness of the design algorithm.

ملخص

إن الشبكات الخلوية القادمة من الجيل الخامس يتم تطويرها بقدرات واعدة تهدف إلى تحقيق سرعات تحميل و كفاءة أفضل من حيث استخدام الترددات والطاقة، و توفر سرعة استجابة أعلى، كما وتخدم أكبر عدد متوقع من المستخدمين وإنترنت الأشياء. يتوقع أن يتم تصميم شبكات الجيل الخامس اعتماداً على استخدام الخلايا الصغيرة عالية الكثافة بجانب خلايا الماكرو أيضاً. هذه البنية ستساعد على تخطي مشاكل عدة منها: إنقطاع التغطية الناتج عن إستخدام الإشارات القصيرة (الملليمتر)، كما ستساعد على تخطي مشكلة الحاجة للحصول على سرعات تحميل مرتفعة، و تخطي مشكلة التزايد في أعداد المستخدمين الفاعلين على الشبكة. إن هذا النوع من الشبكات عالية الكثافة التي تعتمد على إستخدام أعداد هائلة من الخلايا الصغيرة وخلايا الماكرو سوف يؤثر بشكل كبير على إحتياجات الشبكة الخلوية من الطاقة الأمر الذي يستدعي بالضرورة إيجاد طريقة عملية يتم من خلالها التحكم بإستهلاك الطاقة عن طريق التحكم الديناميكي بنظام توفير الطاقة في الشبكات الخلوية.

في هذه الأطروحة قمت بتطوير خوارزمية للتحكم بإستهلاك الطاقة في نموذج إفتراضي لشبكات الجيل الخامس، و قمت من خلالها بالعمل على تقليص الكمية المستهلكة من الطاقة مع الحفاظ على تغطية الشبكة وكفاءة الخدمة المقدمة للمستخدم. تم تصميم نموذج الشبكة الافتراضي على شكل مخطط مما يتيح لنا إستعمال خصائص نظرية المخططات لبناء الخوارزمية المثلى لإستهلاك الطاقة. إن ترابط المخطط طريقة مهمة لضمان تغطية الشبكة ولذلك فإن الخوارزمية أيضا تضمن ترابط الشبكة وتقوم بقياسه عن طريق الترابط الجبري. بواسطة هذه الخوارزمية الإبداعية يتم توفير الطاقة في هذا النوع من الشبكات المتداخلة عالية الكثافة وتتميز هذه الخوارزمية بأنها ذاتية التشغيل وتعمل باستعمال قاعدة بيانات مركزية وبدون تعقيدات إضافية على بنية الشبكة.

تمكنا من خلال الخوارزمية المقترحة توفير نسبة ٢١٪ من الطاقة المستخدمة في وقت إرتفاع الضغط على الشبكة أي ساعات الذروة اليومية، وتوفير ٦٠٪ في وقت إنخفاض الضغط على الشبكة، هذا التوفير يأتي من الطاقة التشغيلية لمحطات بث الخلايا الصغيرة وخلايا الماكرو وخطوط الربط بينهما.

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For my little children Lilas, Zain and Jamal who inspire me with joy and love.

Thank you.
Author
Mosheer Da'as

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List of Abbreviations

3GPP	**T**hird **G**eneration **P**artnership **P**roject
5G	**F**ifth **G**eneration
AuC	**A**uthentication **C**enter
BBU	**B**ase **B**and **U**nit
BS	**B**ase **S**tation
CA	**C**arrier **A**ggregation
CC	**C**onnected **C**omponents
cmWave	**c**enti- **m**eter **W**ave
CRAN	**C**loud **RAN**
D2D	**D**evice **t**o **D**evice
FTTH	**F**iber **T**o **T**he **H**ome
GSM	**G**lobal **M**obile **S**ystem
HeNB	**H**etrogenous **e**volved **N**odeB
HetNet	**Het**rogenous **Net**work
HSS	**H**ome **S**ubscriber **S**erver
ICT	**I**nformation and **C**ommunications **T**echnology
IoT	**I**nternet of **T**hings
IP	**I**nternet **P**rotocol
ISD	**I**nter- **S**ite **D**istance
ITU	**I**nternational **T**elecommunication **U**nion
LTE	**L**ong **T**erm **E**volution
LTE-A	**L**ong **T**erm **E**volution **A**dvanced
MBS	**M**acro **B**ase **S**tation
MeNB	**M**acro **e**volved **N**odeB
µeNB	**M**icro **e**volved **N**odeB
METIS	**M**obile and Wireless Communications **E**nablers for **T**wenty-Twenty **I**nformation
MIMO	**M**ulti **I**nput **M**ulti **O**utput
MME	**M**obility **M**anagement **E**ntity
mmWave	**m**illi- **m**eter **W**ave
MTC	**M**achine **T**ype **C**ommunication
NFV	**N**etwork **F**unctions **V**irtualization
PA	**P**ower **A**mplifier
PDN-GW	**P**acket **D**ata **N**etwork **G**ate**W**ay
PeNB	**P**ico **e**volved **N**odeB
QoS	**Q**uality **o**f **S**ervice
RAN	**R**adio **A**ccess **N**etwork
RAT	**R**adio **A**ccess **T**echnology
RF	**R**adio **F**requency
RRH	**R**emote **R**adio **H**ead
SC	**S**mall **C**ell
SDF	**S**oftware **D**efined **F**unctions
SDN	**S**oftware **D**efined **N**etwork
S-GW	**S**erving **G**ate**W**ay

Small-GW	**S**mall-cell **G**ate**W**ay
SON	**S**elf **O**rganized **N**etworks
UDN	**U**ltra **D**ense **N**etworks
UE	**U**ser **E**quipement
UHF	**U**ltra **H**igh **F**requency
WCDMA	**W**ide **C**ode **D**ivision **M**ultiple **A**ccess
WLAN	**W**ireless **L**ocal **A**rea **N**etwork
WWWW	**W**orld **W**ide **W**ireless **W**eb

Chapter 1

INTRODUCTION

1.1 Background

Next generation 5G standards are being developed by international standard organizations such as Third Generation Project (3GPP) and International Telecommunication Union (ITU). Commercial 5G networks based on ITU standards are expected to be available in 2020, with the number of forecasted subscriptions reaching around 550 million by the end of 2022. It is expected that total mobile data traffic will increase by 45% compared with 2016, and the data traffic per smart phone in Middle East region will reach 7.6 GB/month in 2022. 5G is one of the most anticipated advances in the Information and Communication Technology (ICT) industry. The introduction of 5G will accelerate transformation in many industry verticals, enabling new use cases in areas such as automation, IoT and big data. It is expected that most operators will introduce 5G from 2020, which is closely linked to the time-line for 5G standardization. Early deployments of pre-standard networks are anticipated in selected markets [1] [2].

As of today, there are around 30 operators that have publicly announced 5G introduction plans, with several trials already taking place. Rollout is expected to commence in metropolitan and urban areas, and is forecasted to reach around 10% of population coverage by 2022. Huge demands are coming on current Long Term Evolution (LTE) networks from new user behaviors such as on-demand video, online gaming, and live streaming due to the increased use of smart phones, in addition to the expected demand from digital transformation and IoT. It is forecasted to have around 29 billion connected devices by 2022, of which around 18 billion will be related to IoT [1] [2], this puts more focus on next generation mobile networks.

The key drivers for expanding cellular network coverage and capacity are the exponential rise of smart-phone and mobile broadband usage, coming from the growing numbers of new subscribers in developing markets and the introduction of cellular IoT services in several applications such as smart homes, autonomous driving, remote medical applications, etc [1] [3].

The drivers for traffic growth in mobile broadband networks can be summarized in two words: social and video. Data collected in 2015 shows that in every single minute of the day, nearly 140,000 hours of video were being watched on YouTube, 360 GB of data were being uploaded to Facebook, and more than 13 million WhatsApp messages were being sent [3]. Clearly these sorts of statistics represent significant new demands on mobile networks [1] [3].

In preparation to 5G, operators in mobile technology should cater for the continued subscriber growth, and the shift for video and social media requirements, this puts new demands on the cellular networks and requires innovation in hardware and software design that can deliver higher capacity and better performance, improving the efficiency and cost by simplifying network architecture, and optimizing network solutions for new application areas such as IoT [1] [2] [3].

Practically, mobile networks design for next generation applications should be "3xmulti": multi-standard, multi-band, multi-layer as illustrated in Figure 1.1. Currently, most operators already operate on three technology standards, Global Mobile System (GSM), Wide Band Code Division Multiple Access (WCDMA), and LTE. Operators are planning for 5G introduction, this requires interworking between the standards. It is also required to support multi-band operations as additional licensed and un-licensed bands are becoming available to support the increasing demand on data rates, coverage, and capacity for the coming years. Furthermore, to get the maximum performance out of each band, operators will need multi-layer deployments with a combination of macro and integrated small cells as shown in Figure 1.2 which will enable them to successfully serve high dense indoor and outdoor areas [2] [3].

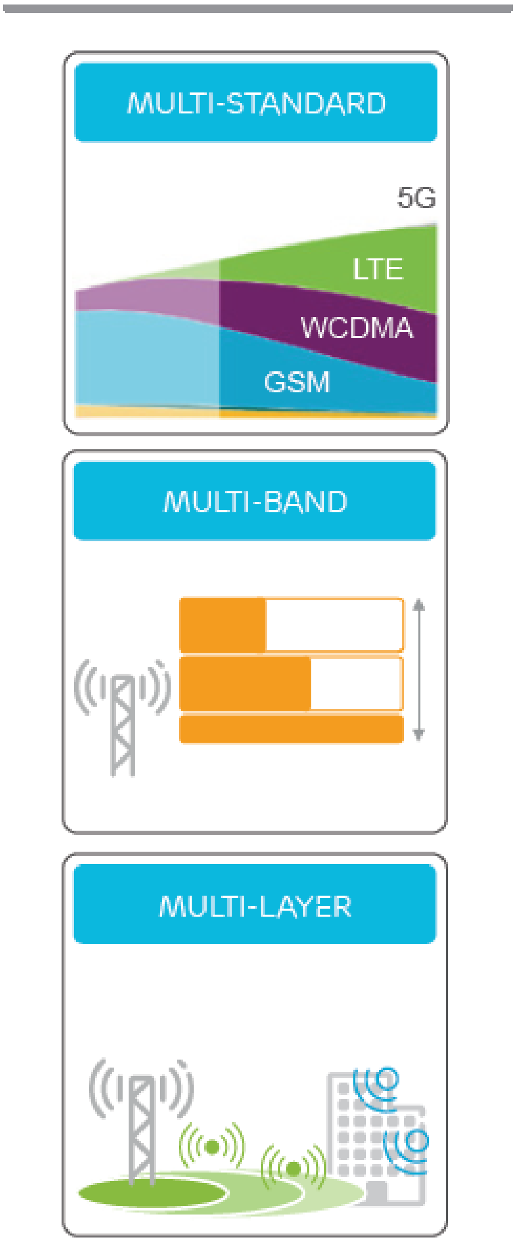


FIGURE 1.1: 3xMulti Concept in Cellular Networks [3]

Geographical areas can be classified according to the density of subscribers and the traffic generated from that area into: Rural, Suburban, Urban, Dense Urban areas as illustrated in Figure 1.2. Different radio design approaches are followed depending on the type of the area under design. For rural and suburban areas the use of macro cells can serve the demand; however, in urban and dense urban areas the small cells are integrated with macro cells to serve required user experience [3] [4].

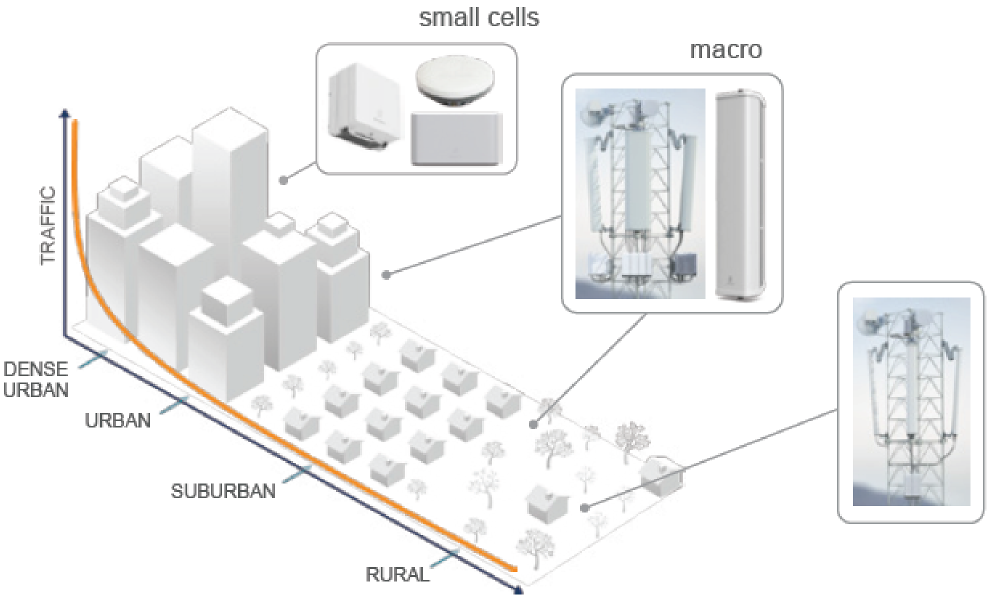


FIGURE 1.2: Types of Geographical Area and Radio Design [3]

The multi-layer deployments, by combining macro cells and integrated small cells, help meet the challenge of maintaining and improving cell edge and in-building coverage for excellent user experience. The greatest demand for high-speed mobile data services and app coverage is often from indoors. A key solution in this area is the deployment of cost-efficient small cells. Small cells are needed in areas where immediate coverage is shielded or lacking (such as inside buildings) or where there is too much traffic for a macro cell to handle (such as in-building areas, street-level traffic, shopping malls, event venues, airports and train stations). Often in dense urban or urban environments, macro network may not be able to offer the required coverage and throughput, thus we need to take a new approach for indoor network design. Small cells alone improve the network performance in certain areas, but integrated small cells (macro and small cells combined) deliver even higher capacity and peak rates, with the potential to improve performance in the macro network by offloading traffic [3] [5] [6].

Unlike other generations of mobile cellular technology, 5G is designed from the start to interwork with evolved versions of current standards, most notably LTE and LTE-Advanced (LTE-A). 5G is not just about a new Radio Access Technology (RAT); it is a combination of a new 5G RAT in new higher frequency spectrum [3], together with evolved LTE, transmission, core networks and services. This will enable operators to quickly introduce 5G in parts of their networks and rely on the evolved LTE functionality in the rest of their network to provide high-quality fallback for early users of the new technologies. Operators will need to be able to quickly and cost-effectively introduce a large number of new applications and services. Network virtualization and abstraction capabilities such as Network Functions Virtualization (NFV), Software Defined Networking (SDN), Cloud Radio Access Network (CRAN), will all have key roles to play [5].

IoT is an enabler for a very wide variety of applications, each of which has different requirements that must be met to make them viable. They can be split into two main classes: massive Machine-Type Communication (MTC) and critical MTC as displayed in Figure 1.3. For massive MTC, it's all about high volumes, involving huge number of devices. For critical MTC, the focus is on safety, security, integrity and low latency, where trust in the system is essential – remote surgery or automated vehicle braking, for instance. 3GPP standard has mechanisms for priority access to certain traffic classes as part of Quality of Service (QoS) configuration, and it supports secure traffic authentication and encryption [3] [4] [5].

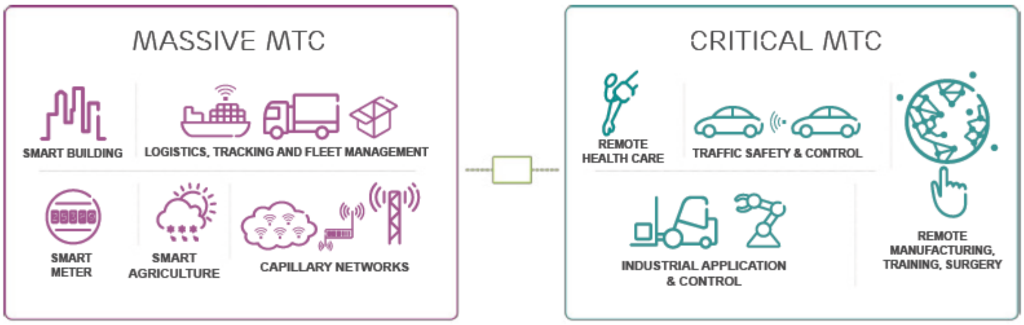


FIGURE 1.3: Massive and Critical MTC [3]

1.1.1 5G Network Architecture and Key Technologies

The next generation 5G RAN system will mainly be an integrated or a converged technology of evolved and revolved multiple cooperating RATs [2] [3] [4]. That is, the architecture of the 5G RAN system will be made up of evolved versions of GSM, WCDMA, LTE, Wireless Local Area Networks (WLAN), MTCs, Fibre To The Home (FTTH), and others. Such evolved and different RATs of dynamic cell sizes will qualify the 5G RAN systems to become a true World Wide Wireless Web (WWWW) system [5].

Furthermore, technical insights drawn from Figure 1.4 and recent research trends reveal that the 5G RAN systems will consist of multiple tiers of Heterogeneous Networks (HetNets). Each tier will have different sizes defined by different RAT Base Stations (BSs) having asymmetrical transmit powers as well as complex interference dynamics down/upstream of macro cells. As illustrated in Figure 1.4, the architecture of the 5G RAN systems will consist of macro and small cells (i.e., micro cell, pico cell, femto cell, relay and Device to Device (D2D)) based communication tiers, each of different RATs [5] [6].

Typically, the Macro evolved NodeBs (MeNBs) are high power base stations with transmit powers close to 43 dBm. The MeNBs are suited to wide area applications such as communication coverage for the remote and rural areas. The Micro evolved NodeBs (μeNBs) and Pico evolved NodeBs (PeNBs) are low power base stations whose transmit power ranges from 23 dBm to 30 dBm. Thus, because of their fairly short distances, they are suitable for urban and enterprise applications. The femto cells are consumer-deployable heterogeneous evolved NodeBs (HeNBs) connected to consumers broadband backhaul. The HeNBs may transmit with powers less than 23 dBm and they may also have restricted User Equipement (UE) associations. Relay evolved NodeBs (ReNBs) use the same spectrum as for MeNBs and PeNBs but transmit with powers similar to those of PeNBs [5] [6].

It should further be noted that the 5G RAN systems will adapt to more frequency spectrums (e.g., mmWave or Extremely High Frequency (EHF) band i.e., 30 - 300 GHz or 1-10 mm) in order to satisfy UDN broadband applications. This implies that an aggressive exploration and efficient utilization of the EHF spectrum will complement the use of existing Ultra High Frequency (UHF) (i.e., 300 MHz - 3 GHz) spectrum [4] [5].

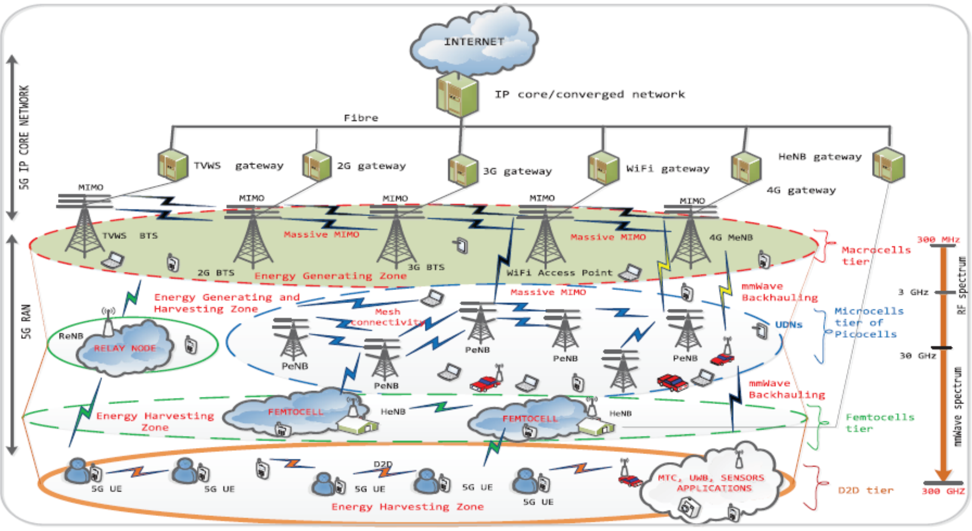


FIGURE 1.4: 5G Network Architecture [5]

To put more focus on resource management issues in 5G UDN, Figure 1.5 represents a simplified network architecture for core and and multi-tier radio 5G network. It describes the inter-working between different radio nodes such as MeNBs, integrated small cells, HeNB, MTC and D2D in radio networks.

The core network is an Internet Protocol (IP) based network transmitting both control signals and data. Core network consists of several components, the Home Subscriber Server (HSS) which is a central database that contains user-related and subscription-related information. The Authentication Center (AuC) is responsible for user's authentication and authorization. The Mobility Management Entity (MME) is in charge of all the control plane functions related to subscriber and session management. The Packet Data Network Gateway (PDN-GW) manage the traffic between home network and foreign networks. PDN-GW is a layer 3 mobility anchor point which is responsible for the IP assignment of the User Equipment (UE). The Serving Gateway (S-GW) is to route and forward the user data packets and it also acts as the layer 2 mobility anchor. The Small-cell Gateway (Small-GW) controls clusters of small cells. The UE connects to the Internet via the eNodeB, the home eNodeB (HeNB), the Relay Station (RS), or the Relay Node (RN) [5] [6].

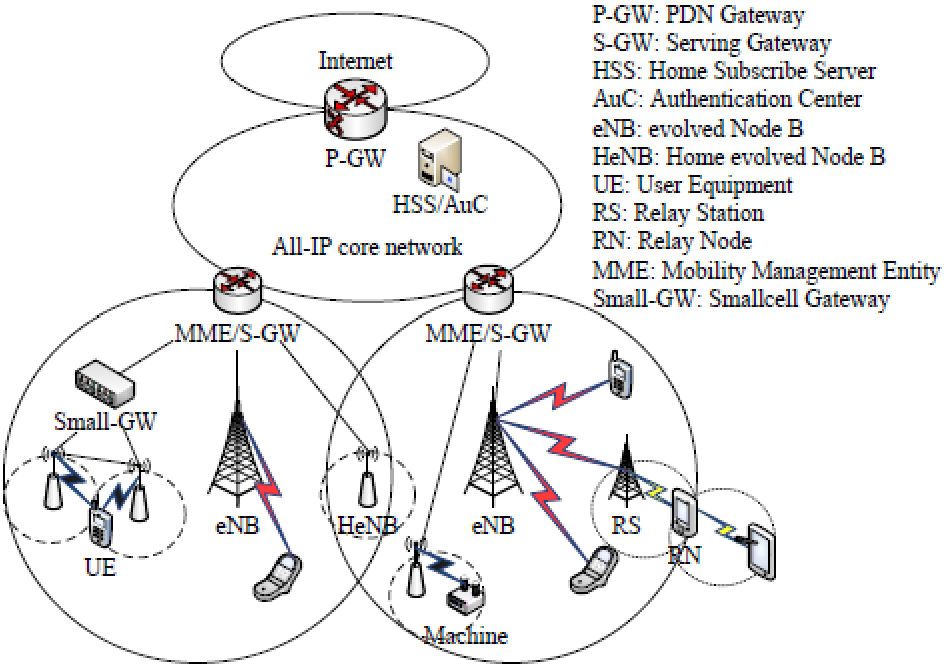


FIGURE 1.5: Simplified 5G Network Architecture [6]

There are several key technologies that will contribute to the development of future 5G networks, some of them are:

- Muli-Input Multi-Output (MIMO)
  The MIMO is a technology to enhance the overall networks performance. MIMO is based on the use of multiple antennas at both the base station and the UE, and it employs several techniques including spatial multiplexing, beam-forming, and pre-coding [7]. In the 3GPP LTE standard, the base station supports 1, 2, 4, and 8 transmission antennas, and the UE supports 1, 2, 4, 8 reception antennas [8] [9].

- Carrier Aggregation (CA) Techniques
  In the 3GPP specifications, CA technique allows aggregation of up to five cells for a UE, and thus it can increase the peak data rates of the UE. CA has been introduced in LTE-A systems to enhance cell edge throughput and can enable UEs to achieve (100 - 300)% higher user throughput [6] [10].

- Software-Defined Network (SDN)
  SDN enables the evolution of Internet with the open flow, network virtualization and service slicing strategies. The wireless networks can obtain benefits from the SDN evolution to fulfill the 5G capacity booming [6]. The basic SDN architecture involves 3 layers namely infrastructure layer, control layer and application layer. In more detail, the infrastructure layer comprises network devices and equipment. The control layer provides “SDN Control Software” and “Network services” for addressing requirements of the applications which are available in the application layer [11].

1.1.2 Importance of Energy Saving in 5G Networks

Energy and spectrum are most important resources in mobile communication, energy consumption is growing significantly. ICT is responsible for about 3% of energy consumption and 2% - 4% of CO_2 emissions in the world [12] [13]. Energy consumption is increasing at a rate of 15% - 20% annually which means double consumption after about 5 years [19], Base stations consume 60% - 80% of the total energy [20] [21], this requires more research on energy management in 5G networks [6].

Mobile and Wireless Communications Enablers for Twenty-Twenty Information Society (METIS) project published the requirements from next generation networks, some of them are: support for hundreds of millions connected devices, 10 to 100 times higher user data rate, 10 times longer battery life, 5 times reduced end-to-end latency, these requirements shall be fulfilled at similar cost and energy dissipation as today. The integration of the new radio concepts such as Massive MIMO, UDN, Direct D2D Communication, Ultra-Reliable Communication, Massive MTC and the exploitation of new spectrum bands will allow to support the expected dramatic increase in the mobile data volume while broadening the range of application domains that mobile communications can support beyond 2020 [22].

In UDN, large number of small cells (i.e., femtocells, picocells) will be deployed to offload the traffic from over-crowed macro cells, this radio densification will significantly improve network capacity by efficient frequency reuse and reducing the distance between BS and UE [6] [23]. While UDN is becoming a key technology towards boosting network performance in terms of capacity, data rate and latency, it also raises the issue of resource management with respect to spectrum and energy efficiency. Even though small cells are of low power compared to macro cells, the sum of energy consumed on ultra-dense small cells network together with the macro cells is non-negligible and brings focus on how to efficiently manage energy consumption in UDN.

Due to the nature of user's distribution in mobile network and the random traffic distribution, it is expected that different BSs will have different load demands, thus some of the small cells and macro cells can be put into sleep mode depending on node utilization [24]. It is a critical problem to optimally determine which set of nodes to put in sleep mode, because of the trade-off between network capacity achieved by network densification and energy efficiency. When turning some of BSs to sleep mode the total number of available network BSs is reduced, this will increase the distance between UE and BS and thus may impact user quality of service such as data rate and latency, to compensate for the increased distances the power transmitted from macro cells (where UE will be reallocated after putting small cell in sleep mode) and the power transmitted from UE should be increased, thus making optimization algorithm more challenging.

In this research, a sample geographical area of 5G UDN is modeled, which consists of macro BSs layer and integrated small cells (pico cells type) layer [2] [3]. Traffic is randomly and uniformlay distributed among the BSs. It is assumed that all pico cell clusters have umbrella coverage from macro BSs [23], thus can compensate for radio coverage when putting small cells into power saving mode [14] [23]. The proposed algorithm has the objective to reduce the total radio network energy consumption by using power off/on method while maintaining the constraints such that radio network coverage continues, BSs maximum capacity should not be exceeded, and required UE QoS should be guaranteed.

Furthermore, the proposed algorithm computes the optimal set of BSs (macro and small cells) to put into power saving mode based on energy efficiency maximization and constraints satisfaction, it is also tested using different experiments. Macro BSs can be put partially in power saving mode depending on their utilization, small cells can be put totally in power saving mode if their utilization is below specified threshold and their traffic can be compensated from macro base stations.

Radio network is modeled as a graph to enable using graph theory in such mobile networks and examine its properties such as centrality measures to identify most important base stations [15]. Graph connectivity is guaranteed through algorithm design and measured using algebraic connectivity [16]. Power saving results are obtained which prove the performance of the proposed algorithm.

1.1.3 Why Using Graph Theory?

Graphs have been used widely to model many types of relations and connections in physics, biological and information systems [14] [25]. Many practical problems can be represented by graphs. Recently due to the advancement in graph theory simulation tools, it is getting more momentum in big data mining and user behavior analysis.

In [26] authors discussed how graph theory is being used as one of the algorithms to deal with big data analysis in social networks such as Facebook, Twitter, Flicker as displayed in Figure 1.6. Although graph theory is being extensively used in social networks, computer networking, and security, but it is still of limited use up to now in mobile networks [25]. Thus it is a focus area for researchers toward 5G molding and development [14], graph theory is used in this thesis for radio network modeling.

FIGURE 1.6: Graph Theory in Social Networks

Complex networks such as UDNs rely for their function and performance on their robustness, i.e. the ability of a network to maintain its connectivity when a fraction of its vertices is damaged. The vertex (or edge) connectivity of a graph is an important measure of robustness of a network. The connectivity represents the ability of graphs to retain connectivity after vertex (or edge) deletion. Thus, it is important while putting radio nodes in power saving mode to monitor the whole network connectivity, this can be achieved using the graph theory properties such as algebraic connectivity [16].

In Graph $G = (V, E)$, nodes are represented as Vertices while links are represented as Edges. In this thesis a weighted undirected graph is used to model the radio network, graph weight reflects user traffic flow over network edges. In the proposed algorithm, the graph connectivity is checked and guaranteed. Graph representation allows nodes/links manipulation easily and gives final representation of network after optimization. Several graph properties such as centrality, connectivity, degree, etc are used during simulation.

1.2 Problem Statements and Motivations

The thesis objectives are to reduce overall radio network energy consumption in 5G networks, and to model multi-layer 5G UDN for energy saving algorithm simulation.

Several constraints are considered while maximizing energy efficiency which are:

1) Radio coverage-hole avoidance.
2) Network connectivity.
3) Demanded QoS.
4) Radio BSs capacity limitations.

The high demands put on 5G networks in terms of energy and spectral efficiency make it of great motivation to research in this area while 5G standardization is still in progress.

1.3 Contributions

Several previous power saving studies conducted on mobile networks are in related work chapter, however, the demands from 5G networks require more advanced procedures to deal with the UDN. The contributions of this thesis are:

- Modeling of next generation 5G UDN using Graph; this helps employing graph theory properties to investigate this kind of complex networks and to have more insights on it.
- Build a novel algorithm to control power saving mode in UDN macro and integrated small BSs.
- The design allows using spectrum recycling from powered-off small cells to increase spectral efficiency.
- The design allows graphical display and monitoring of network BSs, and real-time control of power saving mode in 24h/7d basis.
- Radio network cross-layer and cooperative energy saving mechanism.

1.4 Thesis Organization

The rest of this thesis is organized as follows: Chapter 2 presents related work with discussion on author's methodology and limitations. Chapter 3 describes the design methodology through detailing the UDN network modeling algorithm, problem formulation, and power saving algorithm. Chapter 4 gives performance evaluation by detailing on simulation parameters, simulation results, and then results discussion. Chapter 5 concludes thesis findings and perspectives.

Chapter 2

RELATED WORKS

2.1 Primer on Energy Saving

Several studies published development initiatives related to 5G, each is focusing on specific aspect of next generation networks challenges, researchers are investigating novel methods to satisfy 5G requirements such as higher data rates, reduced latency, number of connected devices and applications, IoT and smart cities, frequency efficiency, millimeter-waves, modulation schemes, energy efficiency, etc [2] [3] [22].

There are several energy efficiency studies in literature, each is focusing on specific area in 5G networks. Figure 2.1 gives an overview of such studies in UE side, radio network, and core network. This thesis focuses on radio network energy saving methods.

5G networks should enable a novel state of the art technology. It is known that 50% of voice calls and 70% of data traffic originate indoors [27] [28]. With the other demands coming from millimeter-waves and high data rates required it is expected that small cells will play important role in 5G architecture. The small cells are low cost, low power, and easy to install nodes. The high number of implemented small cells will convert current heterogeneous networks to ultra-dense networks. With this densification it is requires to have advancement on network management functionalities so that small cells be Self-Organized and Optimized (SON) [29]. The target is to have optimal resources distribution based on the dynamic nature of 5G networks, with the challenges of efficient spectrum allocation, minimum interference and best system load balance, together with less computational complexity and energy consumption.

A centralized downlink frequency planning across small cells and macro cells proposed in [28], but the very large number of small cells may complicate the centralized optimization process. For simplicity, a lagragian relaxation algorithm is introduced in [30] to minimize total energy consumption with constraints on data rate. This algorithm still needs a centralized server to maintain global information of the network and process it, this is very hard in practice due to the large number of small cells in UDN, hierarchical method is preferred to solve such computational issues.

In [6], authors surveyed the resource management issues in UDN such as energy saving and resource allocation problems. Also, they considered resource recycle as one of the future research areas to improve frequency planning in 5G networks. LTE-A supports carrier CA feature in which it is possible to schedule UE on continuous or non-continuous component carriers [31] [32]. In resource recycle, if spectrum utilization of small cell is under a pre-defined threshold, the system could turn off the light loaded small cell and recycle the resource. Fairness problem is also discussed where optimization is required to approximately distribute load over the available carriers.

Regarding energy management issues in BSs, authors in [6] also listed two methods studied in literature [33] - [37], first is dynamic power off/on operation, where light loaded BSs are put in sleep mode, in this method design should effectively deactivate light loaded BSs without ping-pong effect (i.e fluctuation between power off/on modes), moreover, the coverage-hole problem must be avoided [25] [37]. The second method is dynamic power control to adjust node's transmitted power, in this method there were several previous optimization researches, however, their approach might not perform well in complex networks such as UDNs. Another method of power saving was discussed in [6] which is efficient scanning for UE, it describes the trade-off between scanning time and energy consumption.

In [38], authors discussed energy aware computational offloading where energy consumption is reduced by executing jobs on a remote cloud server rather than locally, system was modeled using game theory. Such centralized method can increase signaling load on core nodes and links.

In [39], authors discussed power saving method by energy aware traffic offloading via D2D cooperation. They investigate the cooperative traffic offloading among UEs which are interested in receiving a common content from a cellular BS. The BS first sends the content to some selected UEs which then broadcast the received data to the other UEs, such that each UE can receive the entire content simultaneously. Authors focus on a novel joint optimization of the content transmission rate and each UE's relay-duration, with the objective of minimizing the system energy consumption and the cellular-link usage. Results demonstrate that the optimal UE cooperative offloading can significantly reduce the system cost compared to some heuristic schemes.

In [40], the authors proposed a dynamic channel assignment based on a learning algorithm combined with a BS on/off switching procedure to improve the energy efficiency. The proposed algorithm is self-organizing and performs in distributed manner. Simulation results indicate that the proposed algorithm balances load among BSs and yields better performance compared to the baseline algorithms, however, this algorithm is complex in terms of computational time for the use in UDN.

In [14], authors investigate energy saving in ICT sector, per their study internet consumes 10% of worldwide energy consumption. Their approach is to switch off network's nodes and links while still guaranteeing network connectivity and maximum link utilization. They modeled internet networks using a directed graph, vertices represent routers and edges represent links connecting between routers. The objective is to find the set of routers and links that must be powered on so that the total power consumption is minimized, subject to flow conservation and maximum link utilization. At each power-off step traffic flowing through network element is rerouted on the shortest path, they compared results from several policies: random switch-off, least-link in which sorting was done according to least degree, least-flow in which sorting was done according least traffic flow, opt-edge in which important edges and aggregation nodes are skipped from power-off so connectivity is not exploit. Random and least-flow methods were checked for links. Authors assume off-peak traffic is 20% of peak demand, they repeated experiments for 20 randomly generated network topologies. Comparison between different approaches show that optimum-edge/random and optimum-edge/least-flow for nodes and links respectively are very close to optimum number of switched-off nodes and links. They managed to switch-off around 50% of nodes depending on number of network nodes. This research was limited to the nature of internet networks and it is not applicable to the heterogeneous mobile networks including the 5G networks.

In [23], the authors are targeting to minimize the energy consumption of BSs by optimally controlling the BS's power saving mode, while considering constraints of UEs coverage, capacity of BSs, data rate. They managed to get 38-48% of saving depending on traffic distribution. They modeled UDN hexagonal networks of macro cells, small cells, and UEs. Small cells are considered irregularly deployed under macro cell coverage for traffic offloading. The proposed algorithm determines which BSs to put in sleep mode depending on number of connected UEs to BSs based on geo-location information. When number of connected UEs to BS is zero then BS is switched-off, BS can connect to limited number of UEs to satisfy the throughput constraint. However, this paper focused on number of connected UEs rather than actual traffic generated from UEs, also the complexity of the proposed algorithm is exponentially related to number of UEs and network BSs.

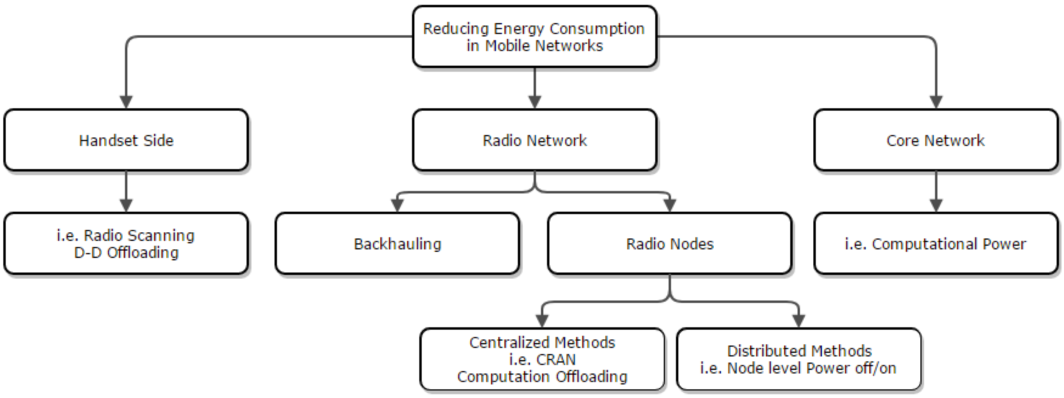


FIGURE 2.1: An Overview of Power Saving Methods in Literature

2.2 Primer on Graph Theory

Graph theory has been applied in different application domains such as social networks and security [25], but researches on using graph theory in mobile networks is still limited [14] [23]. This thesis focuses on graph theory use in modeling 5G mobile complex networks.

In [25], the authors proposed graph theory based network insight analysis framework which can give mobile operators insights about their networks, provide better network coverage, and optimize their infrastructure investments. They focus on network coverage-hole detection and node ranking as two use cases of such framework. Authors built their graph model displayed in Figure 2.2, based on the interactions between physical network information generated from network elements, and UE mobility behaviors generated from mobile application inside the smart phones. The conducted framework includes data mining to produce mobile network graph, global graph view, network analysis based on graph properties. Network hole detection is addressed by the algorithm using the concept of Connected Components (CC) in graph theory, it can discover the isolated CC, nearest neighbors and optimal connectivity for isolated CCs.

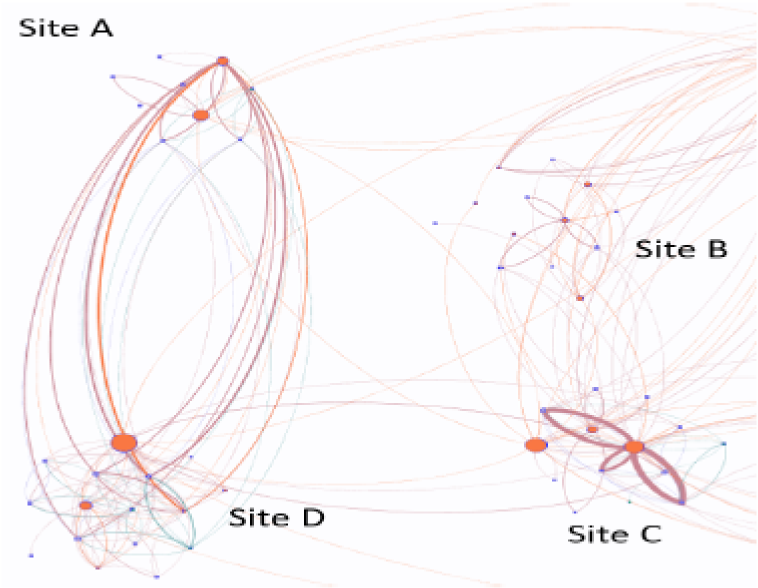


FIGURE 2.2: A Graph Representation of Radio Nodes [25]

In the same study, Node Ranking is addressed with the aim to find how important a node is in the network [25]. Authors used Betweenness Centrality algorithm to find the key sites in a sub-graph.

Graph connectivity in mobile networks is an important measure for network robustness, from which we can find connected radio components and identify isolated components of the graph. There are several methods to calculate graph connectivity, in Section 2.2.2 the algebraic connectivity is discussed in more detais [18].

2.2.1 Graph Properties

This thesis uses graph theory for 5G network model building, and utilizes its properties in energy optimization algorithm. The model uses a weighted un-directed graph to represent radio nodes and links between nodes. Then we use some of graph properties such as centrality and connectivity in energy saving algorithm. In the following, we introduce formal definitions and formulae for some of the graph properties that will be used in the coming chapters [15] [17].

What is a Graph?
A graph $G = (V, E)$ is a collection of nodes and edges that represents relationships between $|V|$ vertices and $|E|$ edges:

- Nodes are vertices V that correspond to objects.

- Edges E are the connections between objects.

The graph edges sometimes have weights making a weighted graph. Graphs can be directed or un-directed depending on their edges type, the following definitions for graphs are detailed:

- **The Un-directed Graphs** have edges that do not have a direction. The edges indicate a two-way relationship, each edge can be traversed in both directions.

- **The Directed Graphs** have edges with direction. The edges indicate a one-way relationship, in that each edge can only be traversed in a single direction. A directed graph is a pair (V, E), where V is the vertex set and E is the set of vertex pairs as in ″usual″ graphs. The difference is that now the elements of E are ordered pairs: the arc from vertex u to vertex v is written as (u, v) and the other pair (v, u) is the opposite direction arc.

- **The Weighted Graph** is a graph for which each edge has an associated weight, usually given by a weight function. In a weighted graph, the weight of a path is the sum of the weights of the edges traversed.

- **Graph Connectivity**. Graph is connected if you can get from any node to any other by following a sequence of edges or any two nodes are connected by a path. A directed graph is strongly connected if there is a directed path from any node to any other node. Algebraic connectivity (detailed in next section) is an important method to measure graph connectivity and identify number of graph connected components.

- **Graph Component**. Every disconnected graph can be split up into a number of connected components.

- **Graph Centrality**. Centrality indices are answers to the question "What characterizes an important vertex?" The answer is given in terms of a real-valued function on the vertices of a graph, where the values produced are expected to provide a ranking which identifies the most important nodes. There are different types of centrality that can be used to identify central nodes, such as degree, closeness, betweenness centrality measures.

- **Degree Centrality**. The degree of the vertex v, written as $d(v)$, is the number of edges with v as an end vertex. By convention, we count a loop twice and parallel edges contribute separately. Let $G = (V, E)$ be a simple graph with $|V|$ vertices and $|E|$ edges; its degree centrality C is:

  $$C_d(G) = deg(G)$$

  $deg(G)$ is the degree of a graph vertex, if the graph is **weighted** graph, then the sum of the edge weights is used rather than the number of connecting edges.

- **Closeness Centrality**. An important node in closeness centrality is typically close to, and can communicate quickly with, the other nodes in the network. The closeness centrality types use the inverse sum of the distance from a node to all other nodes in the graph; the centrality of node C is:

  $$C(i) = (\frac{Ai}{N})^2 \frac{1}{Ci}$$

  Ai is the number of reachable nodes from node i (not counting i), N is the number of nodes in G, and Ci is the sum of distances from node i to all reachable nodes.

- **Betweenness Centrality**. The betweenness centrality type measures how often each graph node appears on a shortest path between two nodes in the graph. Since there can be several shortest paths between two graph nodes s and t, the centrality of node u is:

  $$C(u) = \sum_{s,t \neq u} \frac{n_{st}(u)}{N_{st}}$$

  $n_{st}(u)$ is the number of shortest paths from s to t that pass through node u, and N_{st} is the total number of shortest paths from s to t.

2.2.2 Algebraic Connectivity

"How well connected is a graph?" This is a fundamental question to any problem modeled using graphs and that unfortunately defies a simple answer. Even producing a simple definition as to what well connected exactly means is challenging. The algebraic connectivity – the second smallest eigenvalue of the graph's Laplacian matrix – was established by Fiedler in his seminal work as an elegant answer to this fundamental question [16] [18].

Let $G = (V, E)$ be a simple graph with $|V|$ vertices and $|E|$ edges; its algebraic connectivity is a function of its adjacency and degree matrices. In the following, we introduce formal definitions for all these quantities along with some key results on algebraic connectivity.

Definition 2.2.1 (Adjacency Matrix)**.** Given a simple graph $G = (V, E)$ with $|V| = n$, its adjacency matrix $A(G)$ is a $n \times n$ binary matrix where the entry a_{ij} is equal to 1 if $\{i, j\} \in E$ and 0 otherwise.

Definition 2.2.2 (Degree Matrix)**.** Given a simple graph $G = (V, E)$ with $|V| = n$, its degree matrix $D(G)$ is a $n \times n$ diagonal matrix where the entry d_{ii} is equal to the degree of vertex i.

Definition 2.2.3 (Laplacian Matrix). Given a simple graph $G = (V, E)$ with $|V| = n$, its Laplacian matrix $L(G)$ is a $n \times n$ matrix defined as:

$$L(G) = D(G) - A(G)$$

From Definition 2.2.3, it follows that the entry $l_{i,j}$ of the Laplacian matrix for graph G is

$$l_{i,j} = \begin{cases} deg(i) & \text{if } i = j \\ -1 & \text{if } i \neq j \text{ and } \{i, j\} \in E \\ 0 & \text{otherwise} \end{cases}$$

where $deg(i)$ is the degree of vertex i.

The eigenvalues of the Laplacian matrix are usually referred to as the graph spectra. The number of zero-valued eigenvalues of the Laplacian matrix is equal to the number of connected components in the graph G. Consequently, the *second smallest* eigenvalue being 0 is equivalent to the graph having at least two connected component and thus being disconnected. Therefore, this eigenvalue is referred to as the algebraic connectivity of the graph [16], More formally:

Definition 2.2.4 (Algebraic Connectivity $a(G)$). Let $N \geq 2$ and $0 = \lambda_1 \leq \lambda_2 \cdots \leq \lambda_N$ be the eigenvalues of the Laplacian matrix $L(G)$. The algebraic connectivity $a(G)$ of the graph G is equal to the second smallest eigenvalue, λ_2.

The algebraic connectivity has become essential to the study of the network robustness not only because a non-zero value proves end-to-end connectivity but more importantly because of Lemma 2.2.1 proved by Fiedler [16]. It connects the algebraic connectivity to two important graph properties. One, the *vertex connectivity*, the minimum number of vertices whose deletion from a graph disconnects it. Two, the *edge connectivity*, the minimum number of edges whose deletion from a graph G disconnects it.

Lemma 2.2.1 (Bound on Connectivity). Let $k(G)$ and $\eta(G)$ be the vertex and edge connectivity of the graph G, respectively. Then

$$a(G) \leq k(G) \leq \eta(G).$$

In this thesis, algebraic connectivity is used to determine connected and isolated components in radio network, and to measure graph robustness through its connectivity.

2.3 Primer on UDN Specifications

As stated in [2], 5G small cells deployment in the 6-30 GHz band centi-meter Wave (cmWave) with a 500 MHz carrier bandwidth can provide hundreds of $Gb/s/km^2$ for 2025 and beyond. A 5G small cells deployment in up to 100 GHz bands milli-meter Wave (mmWave) with 2 GHz carrier bandwidth can provide several $Tb/s/km^2$ for 2030 and beyond. For both the cmWave and mmWave deployments, an inter-site distance of 50-100 m can provide full coverage and satisfy the required capacity, depending on the environment. Dedicated indoor small cell deployments are needed to satisfy indoor capacity requirements beyond 2020. METIS test case 2, the Madrid case is deployed with a macro layer having an inter-site distance (ISD) of 250 m and the small cell layer varying between 50, 75, and 100 m ISD [2] [4].

In the efforts of calculating computational power in different types of BSs authors in [41] discussed the computation power ratio increase with the increased number of antennas. Moreover, the computation power ratio of small cell BS is always larger than the computation power ratio of macro cell BS. Based on the results of simulation, the computation power ratio increases with the increase of bandwidth. When millimeter wave technology is adopted, the computation power ratio of small cell BS is obviously larger than 50%.

$$P_{in} = N_{trx}.(P_{stat} + P_{dyn}) \tag{2.1}$$

$$P_{dyn} = ConversionFactor.Load \tag{2.2}$$

Equation 2.1 calculates input power required for a BS with number of Transceivers (TRX) equals N_{trx}, static power per TRX P_{stat}, and dynamic power per TRX P_{dyn}. Pdyn in Equation 2.2 is dependent on BS's $Load$ and UE distances expressed in $ConversionFactor$, it includs the node's computational power which is expected to be higher in small cells compared to macro BSs [41].

Small cells include femtocells of radius up to 100 m, pico cells of radius up to 200 m, in comparison with macro cells of radius up to 1km. The population of small cells is expected to be 100 millions with 500 millions UE in 2020. The power consumption of femto cell now between 5 - 10 W, and 20 - 50 W for Pico cells. The 100 million small cells in 2020 will consume 4.4 TWH assuming 5 W consumption per cell, about 5% increase on top of current networks energy consumption [2] [4].

To improve the energy efficiency of 5G networks with integarted small cells, joint optimization schemes and algorithms should be developed to save computation and transmission power at the Base Band Units (BBUs) and Radio Frequency (RF) chains together as illustarted in Figure 2.3. Authors in [42], breakdown the power consumption in BSs, the power consumption depends on the traffic load; it is mainly the Power Amplifier (PA) consumption that scales down due to the reduced traffic load. They found in macro BSs that 55%-60% of BS's total power consumption at full load is consumed in PA which depends on traffic demand, whereas for low power small cells the PA power consumption has less impact which is around 30% of the total.

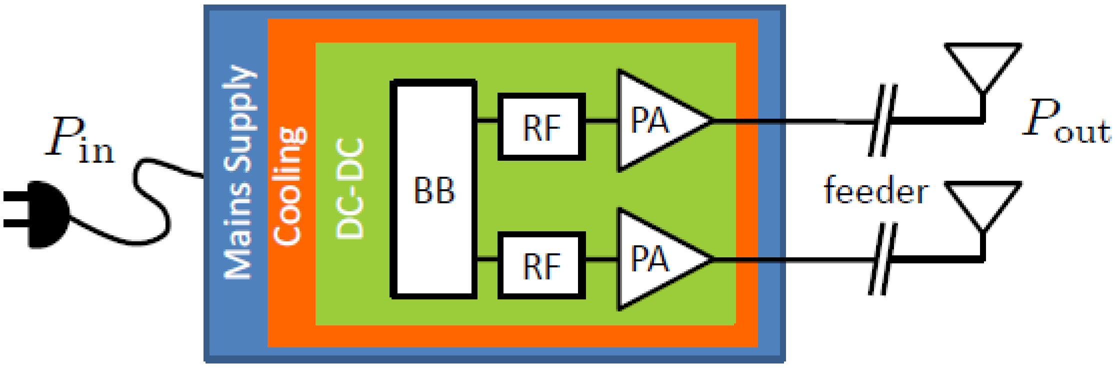


FIGURE 2.3: Block Diagram of BS Hardware Blocks [42]

As a summary of discussed types of BSs (macro, pico, femto) and their specifications (Power consumption, ISD, BS configuration), Table 2.1 shows the BSs specifications derived from LTE systems literature.

TABLE 2.1: BS Power Consumption in LTE Systems with 10MHz Bandwidth and 2X2 MIMO [42] [43]

BS Type	NTRX	Input PWR (w) per TRX	Radius (m)	Max Tx power (dBm)
Macro	6	225	500	43
Pico	2	7.3	100	21
Femto	2	5.2	50	17

On network densification, authors in [11] stated that an operator can deploy around 1000 macro cells for covering a city of a few million inhabitants. And it is expected within the next few years there can be around 100 small cells underlying each macro cell coming from indoor and outdoor small cells; outdoor small cells number can be 2-10 per macro BS in areas of low to considerably high traffic; but, the number can even reach 100 in ultra-high traffic areas [2] [4].

The expected huge number of small cells combined with macro BSs makes 5G networks of complex nature, thus it is required to have new methods for modeling 5G UDN using graph theory, and to put more focus on energy saving efforts.

Chapter 3

METHODOLOGY

3.1 Network Model

In this thesis, a radio **NE**twork m**O**deling algorithm **(NEO)** is designed for 5G UDN simulation. A hierarchical mobile radio network topology is built using Matlab, it is illustrated by a graph of four layers: core nodes, aggregation nodes, Macro Base Stations (MBS), and Small Cells (SC). SCs in this project are considered as Pico cells, the unlicensed SCs (Femto cells) are not included in this model as they are expected to be plug and play low power cells operated by end user [27] [28].

Core nodes are composed of few nodes representing MME/S-GW nodes, and interconnected by high capacity bi-directional links in mesh connectivity for very high availability which reflects actual mobile operators topology as presented in Figure 3.1. Aggregation nodes are MBSs combined with hub transmission equipment used to aggregate traffic from clusters of MBSs and SCs of random sizes, each aggregation node is connected to all core nodes and to the two closest aggregation nodes for redundancy by high capacity bi-directional links.

MBSs and SCs are radio edge nodes used for radio coverage, SCs have less power consumption and coverage area compared to MBSs [40] [42] [43]. Moreover, in this model each SC cluster coverage is overlapped by a MBS coverage [23]. SC clusters are connected to core network through randomly selected MBS or aggregation nodes. Connection links of MBS and SCs to aggregation nodes are of medium capacity and all links are bi-directional.

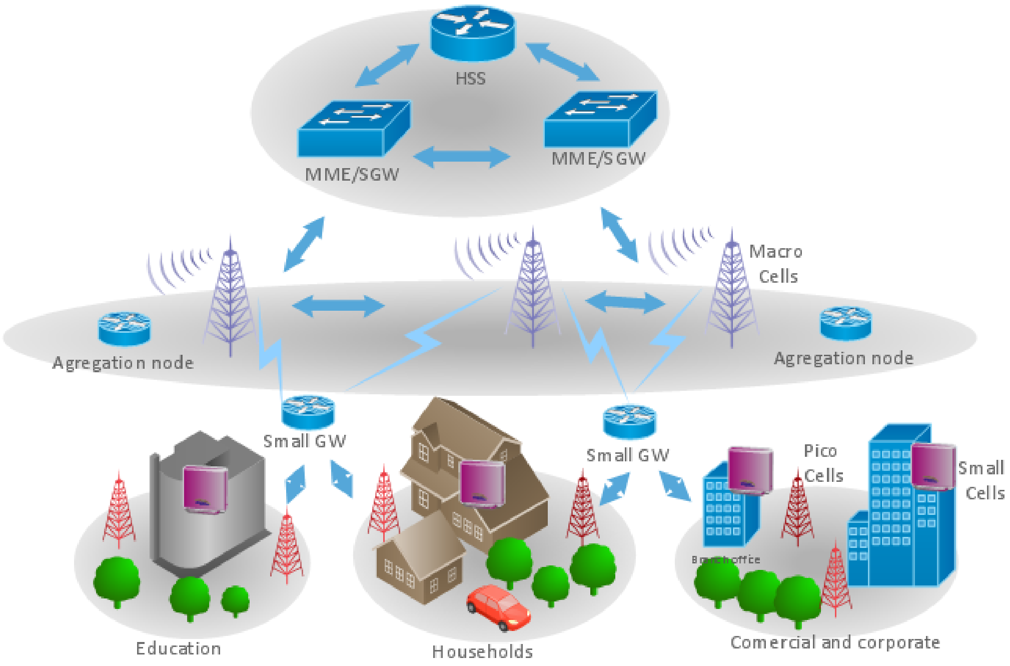


FIGURE 3.1: 5G Network Illustration

The Network Model consists of randomly generated network diagram of 2000 radio nodes, 100 of the total nodes are MBS of three sectors and two TRXs per sector (3*2), 10% of the MBSs are aggregation nodes that provide nodal connection for MBS/SC clusters. The remaining number of total nodes which is 1900 are SCs with omni-directional antennas and two TRXs, number of core nodes is assumed to be 4 MME/S-GW nodes.

NEO distributes MBSs in clusters of random number of (9-15) nodes served by one aggregation node, while number of SCs per MBS is (6-50) distributed over 100 SC clusters as illustrated in Figure 3.2. Randomization of number of SCs and MBSs per cluster helps to design a variable and un-biased network model where number of nodes depends on the geographical area and users density per km^2.

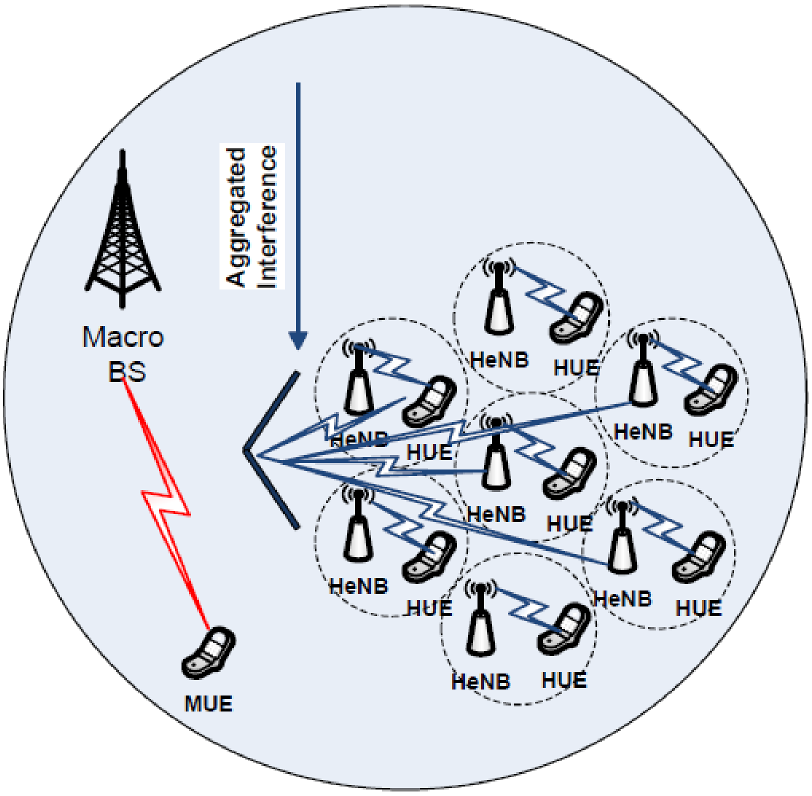


FIGURE 3.2: Illustration of a Small Cell Cluster [44]

Network model coding and simulation is performed through Matlab. Figure 3.3 displays a random run of **NEO**. Figure 3.4 displays a zoomed-in view for the radio network, the model generated is used as input for the power saving algorithm.

The network is represented in a Graph G using Graph theory. $G = (V, E)$, where V: Vertices represent core and radio nodes, and E: Edges represent backbone links between nodes. Edges are weighted, the weight reflects how important is the link for connecting two nodes expressed by link load.

The Graph G is un-directed which enables traffic flow in both directions. The Vertices and Edges have a pre-set maximum capacity values. The maximum capacity for node i is $Cimax$. The maximum link capacity of a link connecting between node i and node j is $Cijmax$. Those maximum capacity parameters are used as limiting boundaries for the random traffic distribution function over the network.

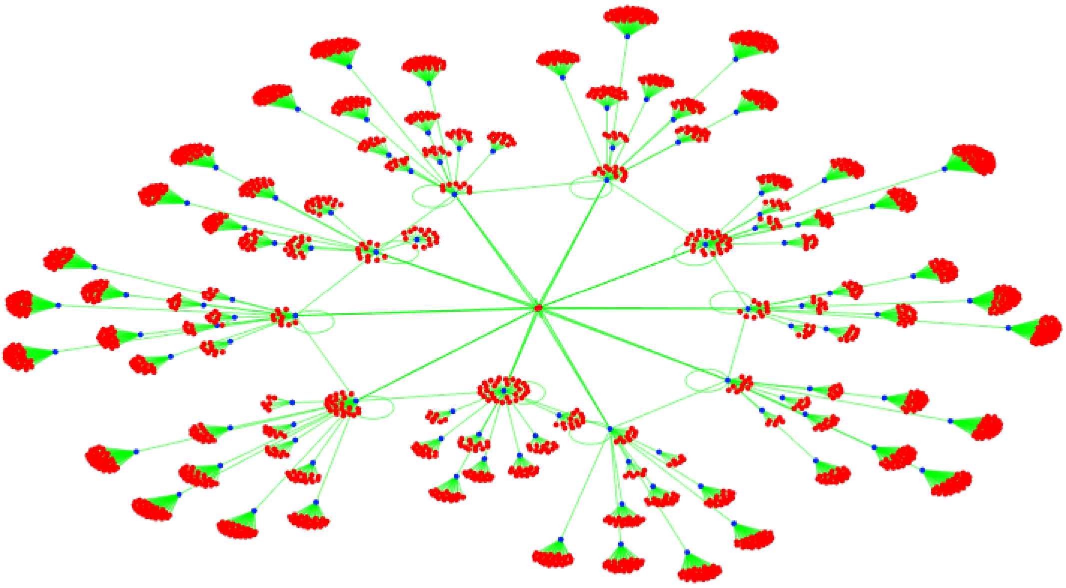


FIGURE 3.3: Nodes and Edges Representation for a Random Run of **NEO**

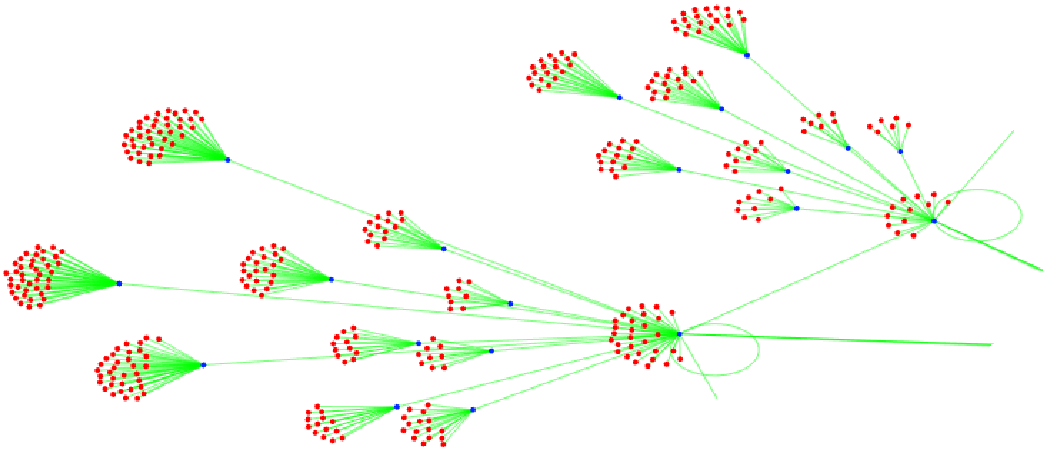


FIGURE 3.4: A Random Run of **NEO**/ Zoom-in

The load on Vertices and Edges is randomly distributed using uniform distribution that is bounded between (30% - 90%) of maximum capacity for MBSs, and (30% - 70%) for SCs, these boundaries help achieve a load optimized radio network design. The maximum capacity of a (3 sector * 2 TRX) MBS/aggregation node $Cimax$ is assumed 10 times the maximum capacity of a (1 sector * 2 TRX) SC $Cjmax$.

Similarly the load on Edges between nodes equals the load on their connected Vertices, the load on Edge connecting between aggregation node cluster and core nodes equals total traffic coming from MBSs and SCs under this cluster divided by number of Edges connecting the cluster to core nodes. Edges are dimensioned to carry the full capacity of connected nodes.

Node's utilization percentage is a measure to reflect node's load to its capacity, it is calculated for all nodes under Graph G, node's utilization will be an important input for Power Saving Algorithm. Figure 3.5 illustrates radio node's load and utilization in simulation model, from the figure it is clear that MBSs have utilization between (30% to 90%) while SC's utilization is between (30% to 70%) as required by design above. MBS node's size reflect BS's load which is greater than SCs as shown in the figure.

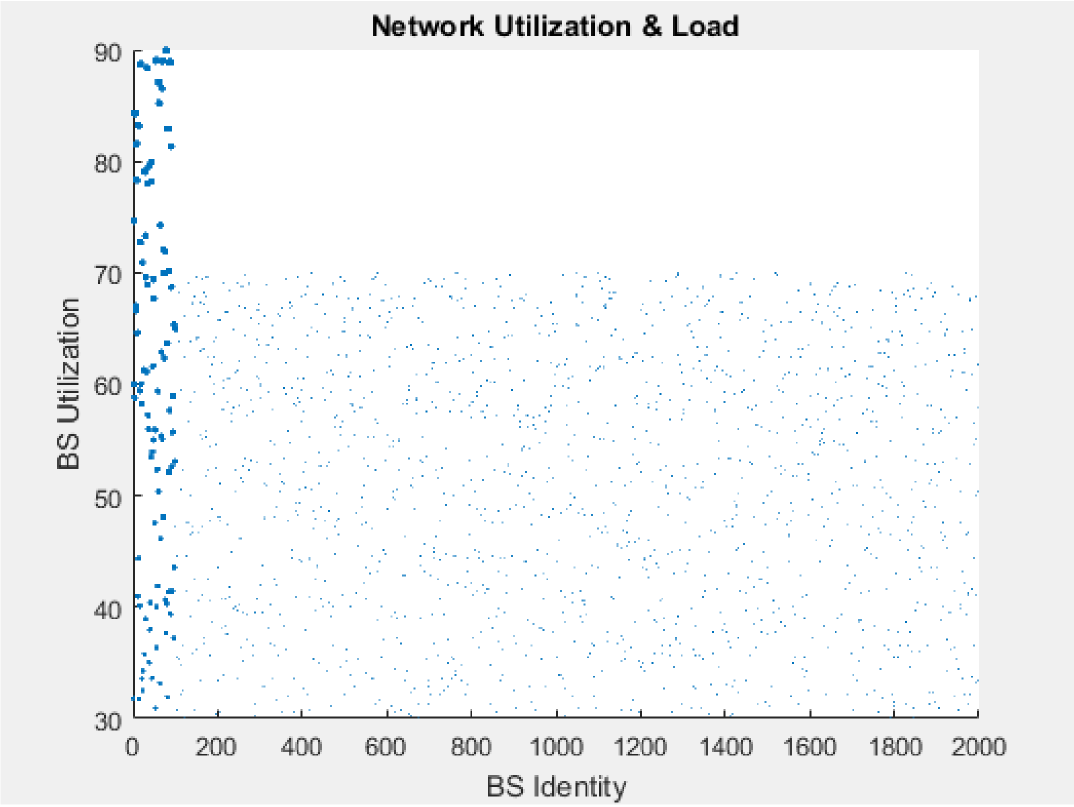


FIGURE 3.5: Network Utilization and Load Before Power Saving. Y-axis represents base station utilization, nodes' size represents base station traffic volume.

Power consumption on node i (Pi) is much greater on MBSs than SCs, this comes from the fact that SCs can be installed without cooling. Besides SCs operate in high capacity but short distances which reduces required signal transmitted power [40] [42] [43].

The total power consumption for a (3 * 2) MBS or aggregation node is assumed to be 1200 watt at full load as shown in Table 3.1. The static power consumption is asumed 80% of the total power, the remaining 20% is for dynamic power consumpion in digital unit. In a (1 * 2) SC, the total power consumption is assumed to be 20 watt at full load as shown in Table 3.1, 40% of the total is for static power and the remaining 60% is for dynamic power. Dynamic power consumption is directly proportional to node's load and reaches its maximum value at full load [42] [43].

Power consumption on edge connecting between node i and node j is Pij, which consists of static and dynamic parts, dynamic power consumption on edges is also directly proportional to link's load. Although both node and link power savings will be considered, it is assumed that power consumption on nodes is much greater than power consumption on links as shown in Equation 3.1 [14]:

$$Pi >> Pij \tag{3.1}$$

Total power consumption values on links used in Network Model are assumed: 100 watt between core nodes, 70 watt between aggregation nodes and core or on aggregation nodes ring, 50 watt between aggregation nodes and MBSs, 10 watt between MBSs and SCs.

More parameters and design values are listed in Table 3.1, these parameters are used in own Network Model derived from literature values in Chapter 2 .

TABLE 3.1: Network Model Parameter Values

Properties	*Cell Type*		
	Macro	**Pico**	**Femto**
Power	43dBm	30dBm	20dBm
ISD (m)	500	100	50
Deployment	outdoor	Indoor & Outdoor	Indoor
Installation	By operator	By operator	operator, end user
Cost	Expensive	Medium	Cheap
Frequency Band	2GHz	cm-wave/ mm-wave	mm-wave
Capacity	High	Very High	Very High
Antenna	3 sectors of 2 TRX each	Omni directional 2 TRX	Omni directional 1TRX
Total Input Power (w)	1200	20	5
Portion of Pstat at full load	80%	40%	40%

3.2 Problem Formulation

This research considers putting partial parts of MBSs in sleep mode during daily operation by deactivating number of TRXs depending on traffic demand using power saving mode on nodes. This saves from the static power of MBSs. On the other hand, SC BS as a whole node will be put in power saving mode depending on its utilization, thus saving its static power. However, SC's load will be migrated to its covering upper node (MBS or aggregation) while capacity constraint is not exceeded. This implies a slight increase in dynamic power consumption for the migrated traffic from SC to MBS due to the increased signal transmission distance [4], but the total power consumption should decrease as will be explained in this section.

Power saving on edges happen only when a SC is put in power saving mode, then the static power consumed on connecting Edge is saved. None of the Edges connecting between MBSs to core network or Aggregation ring is allowed to be in power saving mode, this is vital to keep network connected.

Dynamic power consumption on MBS, SCs and their links is proportional to their carried traffic, Dynamic power for each type is calculated by multiplying the unit load values with normalization factor to compute dynamic power consumption in watt. The normalization factors α, β and γ are for MBSs, SCs, and Links, respectively.

While turning off nodes, the following constraints should be maintained:

1) Radio coverage-hole avoidance.
2) Network connectivity.
3) User demanded QoS.
4) Radio node capacity limitations.

Data mining in real networks should be automatically run on centralized Operations and Maintenance System fed by traffic statistics from network nodes and links periodically (24H/7Days).

Below equations formulate the power calculations in watt. Equation 3.2 is used to calculate the total power consumption in radio node i. Equations 3.3 and 3.4 are used to calculate power consumption in MBS and SC nodes, respectively. Power consumption on backbone link connecting between node i and node j is calculated in Equation 3.5. Equation 3.6 is used to calculate the total power consumption in N radio nodes and n backbone links.

$$P(i) = (P_{stat}(i) + P_{dyn}(i)) \tag{3.2}$$

$$P_{MBS}(i) = (P_{stat}(i) + (\alpha * NodeLoad(i))) \tag{3.3}$$

$$P_{SC}(i) = (P_{stat}(i) + (\beta * NodeLoad(i))) \tag{3.4}$$

$$P(i,j) = (P_{stat}(i,j) + (\gamma * LinkLoad(i,j))) \tag{3.5}$$

$$\begin{aligned} P_{tot} = & \sum_{(i,j)=1}^{n} (x_{i,j} * P(i,j)) \\ & + \sum_{i=1}^{N1} (y_i * P_{MBS}(i)) \\ & + \sum_{i=1}^{N2} (y_i * P_{SC}(i)) \end{aligned} \tag{3.6}$$

$$N = N_1 + N_2 \tag{3.7}$$

where,

N_1: number of macro node.
N_2: number of small cells.
$P(i)$: power consumption on node i.
$P(i,j)$: power consumption on link between node i and node j.
P_{stat}: static power.
P_{tot}: total power consumption from nodes and links.
$x_{i,j}$: equals 1 if link i,j exists.
y_i: equals 1 if node i exists.

The Value of α is at worst case (equals 24) when MBS transmits at maximum dynamic power for users located on long distances, and at best case (equals 12) when UE is very close to MBS similar to SCs normalization factor β.

To calculate the value of β consider a SC with input power = 20 watt, the portion of P_{stat} at full load taken from Table 3.1 equals 40%, so the dynamic power consumed at one SC is $60\% * 20watt = 12watt$, the full load assumed in the model for SC is 1 unit value, using Equation 3.4 the value of $\beta = \frac{P_{dyn}}{UnitLoad} = \frac{12}{1} = 12$. Similarly, to calculate worst case value of α, consider a MBS with total input power equals 1200 watt and full load equals 10 units, the portion of P_{stat} at full load taken from Table 3.1 equals 80%, then the dynamic power consumed at one MBS is $20\% * 1200watt = 240watt$, using Equation 3.3 the worst case value of $\alpha = \frac{P_{dyn}}{UnitLoad} = \frac{240}{10} = 24$. The value of γ can't be directly derived from network parameters and hence is approximated in the range between β and α.

$\alpha = 24$
$\beta = 12$
$\gamma = 15$

Node utilization is the entry criteria for power saving algorithm, several methods will be used in test scenarios for node selection method in which algorithm determines which node to start putting in power saving mode as long as relative maximum capacity constraint is not exceeded.

Power saving mode on MBSs is assumed to reduce node's static power consumption by a maximum of 70%, the minimum maintained power consumption of 30% is to guarantee node radio coverage continuity for low user traffic demand. If MBS's utilization exceeds 30% then node static power is assumed proportional to node's (load/capacity). For simplicity, static power reduction is assumed a continuous function; however, in real networks this function is discrete and depends on number of TRXs per node. On the other hand, in SC power saving, if algorithm determines a node to be in power saving mode, then it will remove the node and its connecting edge from the network graph. This reduces total network static power consumption coming from SC and its connecting edge.

3.3 Energy Management Algorithm

This thesis proposes a novel energy **S**aving algori**T**hm for **5**G utr**A**-dense netwo**R**k **(STAR5)**. **STAR5** aims to maximize power saving by optimizing radio network power-off and power-on procedures. Load Factor LF is a variable used in network model to variate the traffic demand over time on daily bases. At low traffic time, the algorithm assumes that network load is uniformly reduced to 30% of initial randomly-generated traffic profile "$LF = 0.3$" for all radio nodes, **STAR5** relies on two inputs to determine the power saving mechanism: node type and node utilization. It can be split into two parts: Power-off procedure, and Power-on procedure.

3.3.1 Power-Off Procedure

In Power-off procedure illustrated in Flow Chart shown in Figure 3.6, the logic of **STAR5** works as following: if node utilization is less than 70%, power saving on the processed node is activated based on its type, for SCs to put in power saving mode the algorithm checks nearest MBS which provides umbrella coverage to SC area, if the MBS utilization will not exceed 70% when taking over the SC traffic, then SC will be put in sleep mode, algorithm will then migrate SC traffic to the nearest MBS, and re-calculate the power consumption and load distribution in network. In SC power saving, it is the static and dynamic power of SC that are saved, the increase in dynamic power due to traffic migration from SC to MBS is calculated in MBS dynamic power as shown in flow chart in Figure 3.6.

While node utilization is less than 70%, if the node is MBS or aggregation macro node, TRX sleep mode is activated based on node utilization plus 5% to avoid ping-pong effect, a minimum capacity of 35% is guaranteed when node utilization is below 30% so MBS can never be completely powered-off, this is to guarantee radio coverage continuity. If node utilization is more than 30%, an extra 5% capacity over node utilization is guaranteed. Here in this procedure, I assumed that dynamic control of TRX capacity on MBSs is technically possible. In MBS power saving, we save in static power coming from non-utilized TRXs, no change on dynamic power consumption. Then optimization algorithm will re-calculate the power consumption and nodes utilization.

If node utilization of both node types is bounded between (70%-90%), power saving is skipped on those loaded sites to avoid running network over 70% utilization which is a critical point in mobile networks.

For nodes which are running with utilization equals or more than 90%, algorithm activates power-on procedure on those nodes depending on their type, more details in Power-on procedure description section.

STAR5 executes in a loop equals the number of radio nodes in the network, at each iteration it passes over the above-mentioned filters which are designed to guarantee a very controlled power saving procedure to keep continued network connectivity and avoid disconnected components, it also prevents any node/edge from being overloaded due to power saving procedure.

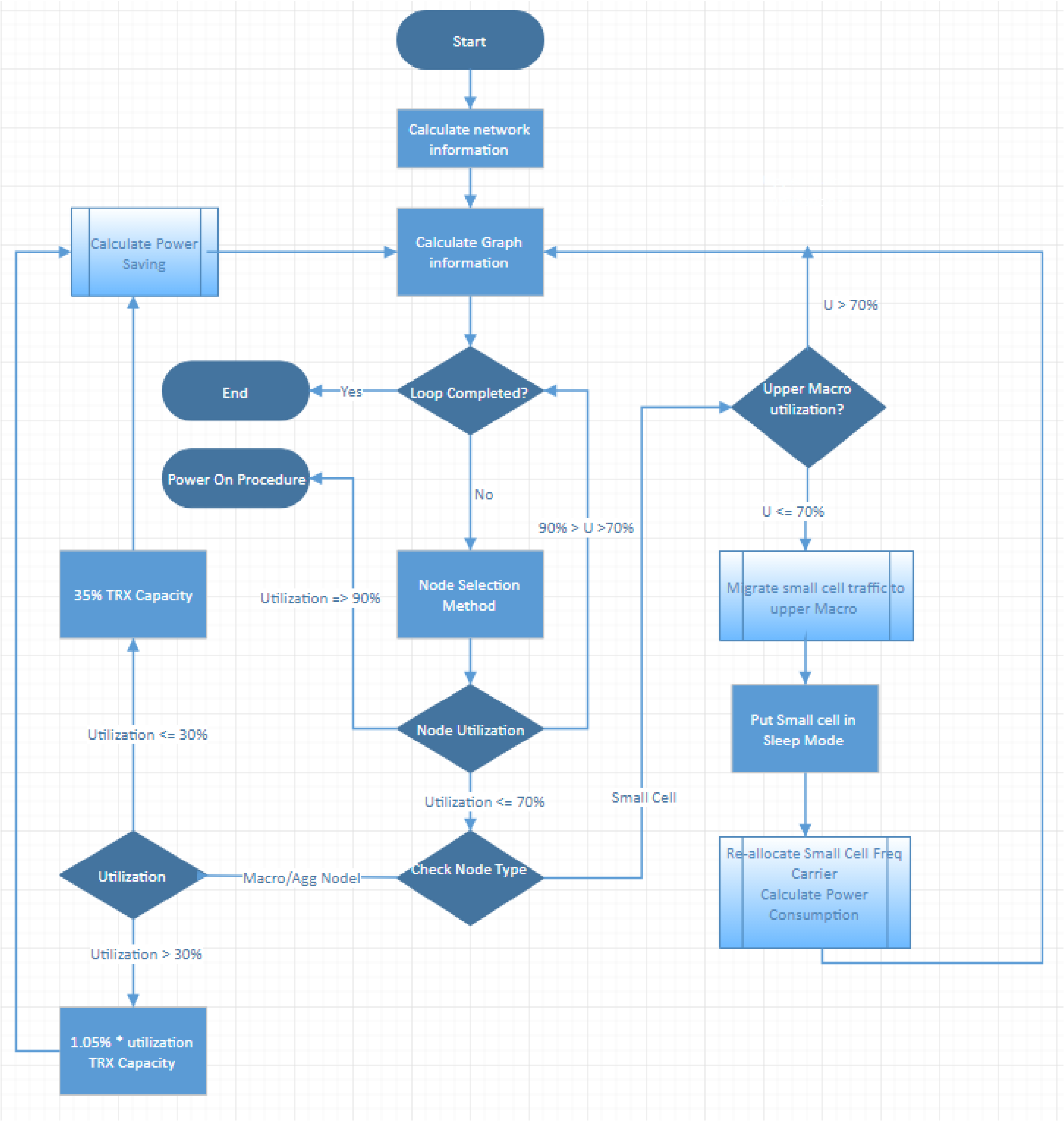


FIGURE 3.6: Flow Chart of **STAR5**/ Power-off

3.3.2 Power-On Procedure

In Power-on procedure illustrated in Flow chart in Figure 3.7, **STAR5** is only activated in case the selected node's utilization equals or exceeds 90%, and the logic works according to node type as following: if node type is SC then Power-on algorithm tries to activate full capacity of TRXs on covering MBS provided the MBS is in power saving mode, algorithm keeps load on SC as minimum as 50% of maximum SC capacity and re-allocates the remaining load to MBS, then it calculates load, utilization and power consumption in the processed nodes. Else, if MBS is not in power saving mode, algorithm activates nearest SC in the same cluster which is in power saving mode to offload processed SC. The load which is kept on processed SC is 50% of its capacity, remaining is assigned to powered on SC. Then load distribution, utilization and power consumption is calculated again.

If node type is MBS, then algorithm activates MBS's full capacity if it was set in power saving mode, else it activates a number of underlying SCs if any in power saving mode to offload covering MBS. Number of SCs required is calculated to offload MBS to 50% of its capacity, then algorithm loads powered on SCs with 50% of their capacity. Additionally, load distribution, node utilization and power consumption are re-calculated.

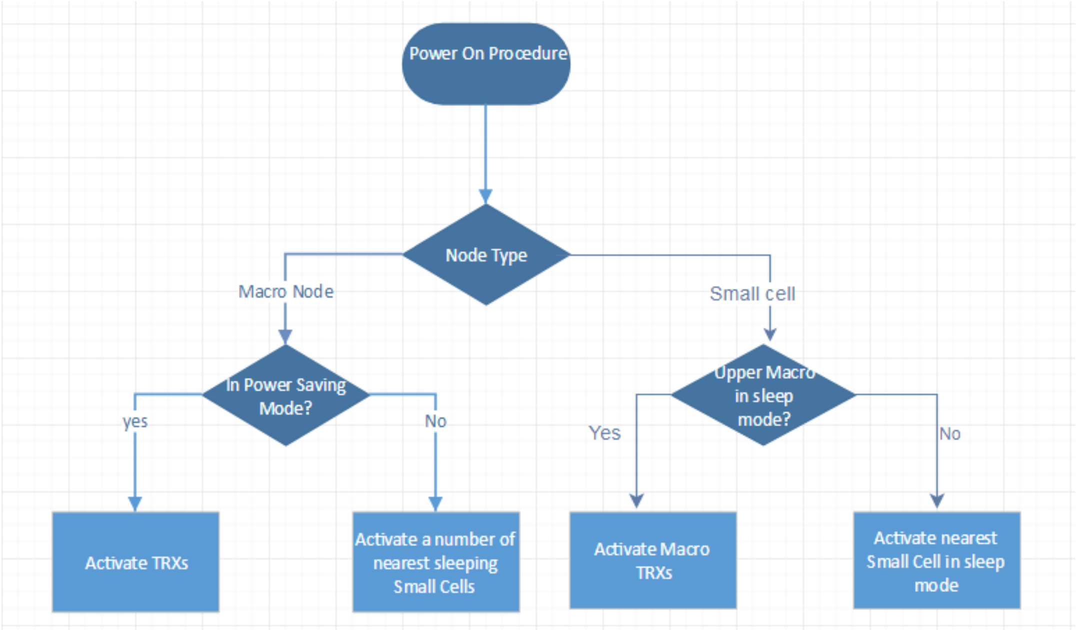


FIGURE 3.7: Flow Chart of **STAR5**/ Power-on

3.3.3 Power Saving Calculations

The saved power is calculated from the differences in power consumption between Graph H for all nodes N and all edges n before power saving, and Graph $H1$ for all nodes $N1$ and all edges $n1$ after power saving. Equations 3.8 and 3.9 calculate dynamic and static power consumption, respectively, for node i in Graph H. Equations 3.10 and 3.11 calculate dynamic and static power consumption, respectively, on link (i,j). Similarly Equations 3.12 - 3.15 do the same above calculations but for Graph $H1$.

$$\begin{aligned} Pn_{dyn} &= \sum_{i=1}^{N} P_{dyn}(i) \\ &= \sum_{i=1}^{N} (H.Nodes.DynNodePower(i)) \end{aligned} \tag{3.8}$$

$$\begin{aligned} Pn_{stat} &= \sum_{i=1}^{N} P_{stat}(i) \\ &= \sum_{i=1}^{N} (H.Nodes.StaticNodePower(i)) \end{aligned} \tag{3.9}$$

$$\begin{aligned} PL_{dyn} &= \sum_{(i,j)=1}^{n} Pij_{dyn} \\ &= \sum_{(i,j)=1}^{n} (H.Edges.DynLinkPower(i,j)) \end{aligned} \tag{3.10}$$

$$\begin{aligned} PL_{stat} &= \sum_{(i,j)=1}^{n} Pij_{stat} \\ &= \sum_{(i,j)=1}^{n} (H.Edges.StaticLinkPower(i,j)) \end{aligned} \tag{3.11}$$

$$\begin{aligned} Pn_{dyn1} &= \sum_{i=1}^{N1} P_{dyn1}(i) \\ &= \sum_{i=1}^{N1} (H1.Nodes.DynNodePower(i)) \end{aligned} \tag{3.12}$$

$$\begin{aligned} Pn_{stat1} &= \sum_{i=1}^{N1} P_{stat1}(i) \\ &= \sum_{i=1}^{N1} (H1.Nodes.StaticNodePower(i)) \end{aligned} \tag{3.13}$$

$$\begin{aligned} PL_{dyn1} &= \sum_{(i,j)=1}^{n1} Pij_{dyn1} \\ &= \sum_{(i,j)=1}^{n1} (H1.Edges.DynLinkPower(i,j)) \end{aligned} \tag{3.14}$$

$$\begin{aligned} PL_{stat1} &= \sum_{(i,j)=1}^{n1} Pij_{stat1} \\ &= \sum_{(i,j)=1}^{n1} (H1.Edges.StaticLinkPower(i,j)) \end{aligned} \tag{3.15}$$

The dynamic power consumption on edges is assumed constant before and after power saving i.e $Pij_{dyn} = Pij_{dyn1}$. This is because the load and γ are not changing, then saving can be calculated by taking the difference in power consumption before and after running **STAR5** as shown in Equations 3.16 and 3.17 as:

$$\begin{aligned} Saving = {} & (Pn_{dyn} - Pn_{dyn1}) \\ & + (Pn_{stat} - Pn_{stat1}) \\ & + (PL_{stat} - PL_{stat1}) \end{aligned} \tag{3.16}$$

$$Saving\% = \frac{Saving}{Pn_{dyn} + Pn_{stat} + PL_{stat}} * 100 \tag{3.17}$$

Chapter 4

PERFORMANCE EVALUATION

4.1 Simulation Parameters

Several experiments were developed to test the performance and robustness of **NEO** and **STAR5**. Experiments tested the different BS selection methods for the power saving algorithm, network load conditions and different utilization plans. Other experiments focused on node type distribution among total nodes, tested the dynamic power variation impact due to varied users distance from MBSs, and measured network connectivity before and after power saving.

4.1.1 Experiment 1: BS Type and Distribution

While fixing node selection method at minimum weighted degree centrality, traffic distribution at off-peak traffic profile, and network type at utilized networks, the variation impact of the following parameters is tested:

- Scenario 1.1: Changing the number of SCs at fixed number of MBSs (100 MBS).
- Scenario 1.2: Changing the number of total nodes with fixed MBS's percentage (10%).
- Scenario 1.3: Changing the MBS's percentage (10% - 70%) while fixing total number of nodes at (2000 nodes).

4.1.2 Experiment 2: Network Utilization

In this experiment the proposed algorithm is verified at different network utilization conditions which reflect different types of radio network capacity planning:

- Scenario 2.1: Comfortable Networks
  In this network type, modeling algorithm distributes load over network BSs at peak time randomly with a maximum utilization boundaries equal 90% of MBS's maximum capacity, and 70% of SC's maximum capacity, with a very low minimum limit of 1%.
- Scenario 2.2: Utilized Networks
  In this network type, the algorithm uses boundaries for the load distribution on network BSs between (30% - 90%) of maximum MBS's capacity, and (30% - 70%) of maximum SC's capacity at peak time, which reflects more utilized and planned network deployments.

4.1.3 Experiment 3: Load Factor Impact

STAR5 is verified under different traffic load conditions, which reflect the traffic demand variation between peak and off-peak times during the day:

- Scenario 3.1: Peak Traffic Profile
  This reflects full load condition which is randomly generated from **NEO** at peak time.
- Scenario 3.2: Off-Peak Traffic Profile
  It reflects the time when load is 30% of the initial peak traffic.
- Scenario 3.3 The 50% Traffic Profile
  It reflects the time when load is 50% of the initial peak traffic.
- Scenario 3.4: The 70% Traffic Profile
  It reflects the time when load is 70% of the initial peak traffic.

  In each traffic profile case above, LF is multiplied by the original load distribution at peak time on all nodes in the network to achieve the target load distribution, uniform load reduction is assumed over the network.

4.1.4 Experiment 4: Dynamic Power Compensation

The different values of α reflect how much compensation in dynamic power is needed to move traffic from SC to MBS, the compensation factor is the difference between α and β calculated by $(\alpha - \beta)$. Differences come from the fact that not all mobile stations are at the same distance from MBS thus different transmission power levels required to serve users at different distances from the BS [4].

Power saving algorithm is tested at different values of α while fixing β value. α is the parameter for dynamic power transmission control, and it is tested with the following values: (12, 16, 20, 24) in this model, where 12 is the best case value when UE is close to the BS and 24 is the worst case value when UE is far from the BS (please refer to Section 3.2 for more details).

4.1.5 Experiment 5: BS Selection Method

In this experiment, **STAR5** is examined using different BS selection methods, the node selected in this criteria is used as input for power saving algorithm, this process is iterative till all nodes are checked, the following methods tested:

- Scenario 5.1: BS Load
  Algorithm in each iteration chooses the node according to its load to apply power saving procedure till it passes over all network nodes.
- Scenario 5.2: Minimum Weighted Degree Centrality
  The 'degree' is a centrality measure for a graph and is based on the number of edges connecting to each node. When using 'Importance' option with edge weights, then the algorithm uses the sum of the edge weights rather than the number of connecting edges [15]. This method selects the node based on minimum weighted degree on nodes which reflects load flow over network edges.

- Scenario 5.3: Node Degree Centrality
  Algorithm selects the node according to degree centrality without using weight function: the number of edges without considering the weight on these edges.
- Scenario 5.4: Random Selection of Nodes
  In this method algorithm selects the node randomly without any preference till it passes over all network nodes.

In all of the above scenarios, graph node's/edge's properties such as load, utilization, power consumption, and centrality are dynamic values and updated in each iteration once there is a change on their values coming from power saving procedure; such changes happen due to traffic migration or node removal from graph when putting SC in sleep mode. Thus each iteration will have an updated graph parameters to be used as input to the selection method.

4.1.6 Experiment 6: Network Connectivity

Connectivity is an important measure in mobile wireless networks, a connected network implies connected radio coverage according to radio design. The number of zero-valued eigenvalues of the Laplacian matrix is equal to the number of connected components in the graph G.

The algebraic connectivity or the second smallest eigenvalue of the Laplacian matrix of a network graph G, is widely studied in the literature due to its importance for the connectivity, it is a basic measure of the robustness of the graph. Literature in [18] showed that the algebraic connectivity measures stability and robustness of the network graph. A network is more robust when the algebraic connectivity of the network is larger.

Algebraic connectivity > 0 if and only if G is a connected graph [16].

4.2 Simulation Results

4.2.1 Experiment 1: BS Type and Distribution

Scenario 1.1: Variation of SCs Impact

With fixing the following simulation parameters, the impact of varying the number of SCs in the network on power saving percentage is tested while fixing the number of MBSs:

- Node selection method is Minimum Weighted Degree Centrality.
- Number of MBSs is fixed at 100 nodes.
- Network type is Utilized Network.
- Off- Peak traffic profile.
- $\alpha = 24$ (worst case value, more details on section 3.2)

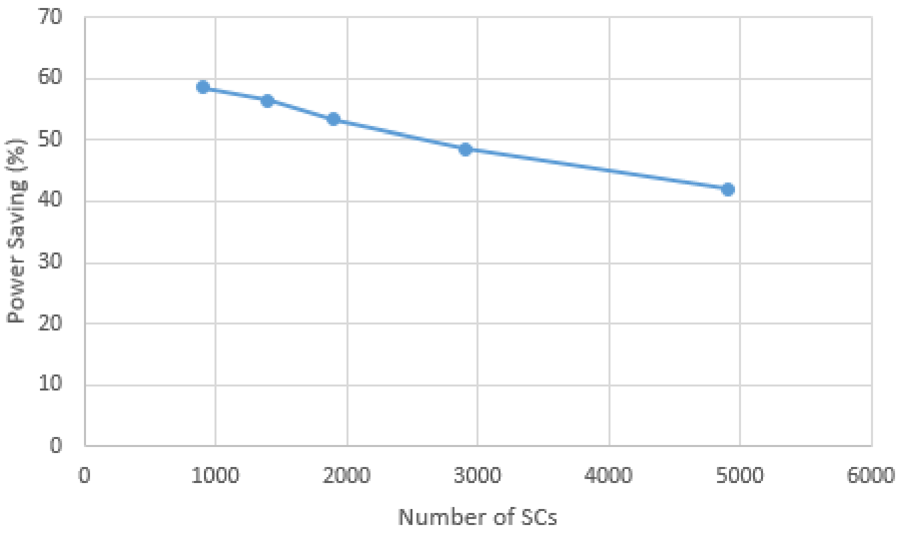


FIGURE 4.1: Power Saving vs. Number of SCs

There is a noticed decrease in power saving percentage when increasing the number of SCs while fixing the number of of MBSs as summarized in Figure 4.1. This behavior can be explained due to the fixed number of MBSs, as the power saving algorithm requires MBSs with utilization below 70% to absorb the traffic from under-laid SCs that will be put in power saving mode.

Scenario 1.2: Total Number of Nodes Impact

With fixing the following simulation parameters, the impact of varying the total number of nodes in the network (network size) on power saving is tested:

- Node selection method is Minimum Weighted Degree Centrality.
- Number of MBSs is 10% of total number of nodes.

- Network type is Utilized Network.
- Off- Peak traffic profile.
- $\alpha = 24$ (worst case value, more details on section 3.2)

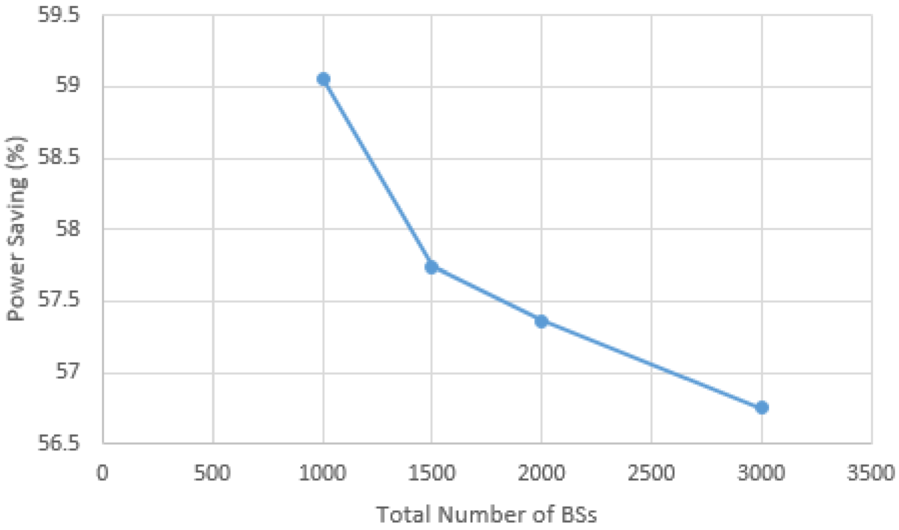


FIGURE 4.2: Power Saving vs. Total Number of BSs

There is a slight decrease in power saving percentage while the total number of nodes increases as can be seen in Figure 4.2. This can be explained as the number of MBSs (10% of the total) may not be enough in large networks to absorb the traffic coming from all underlaid SCs that will be put in power saving mode.

Scenario 1.3: Percentage of MBSs Impact

With fixing the following simulation parameters, the impact of varying the percentage of MBSs in the network on power saving is tested:

- Node selection method is Minimum Weighted Degree Centrality.
- Total number of nodes is 2000 nodes.
- Network type is Utilized Network.
- Off- Peak traffic profile.
- $\alpha = 24$ (worst case value, more details on section 3.2)

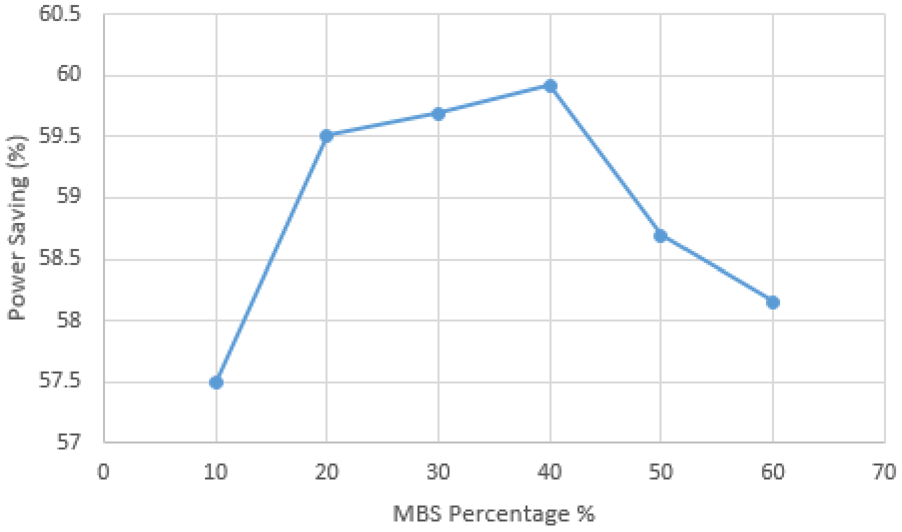


FIGURE 4.3: Power Saving vs. Percentage of MBSs

In general power saving algorithm is giving saving ratio above 57% at all tested MBS percentage points, and it maximizes when MBS ratio is 40% as we can see in Figure 4.3.

4.2.2 Experiment 2: Network Utilization

Different network types imply different behavior on power saving algorithm, with fixing the following simulation parameters, the variation impact of network planing and utilization on power saving algorithm is tested:

- Node selection method is Minimum Weighted Degree Centrality.
- Number of MBSs is 100 nodes.
- Total number of nodes is 2000 nodes.
- Off- Peak traffic profile.
- $\alpha = 24$ (worst case value, more details on section 3.2)

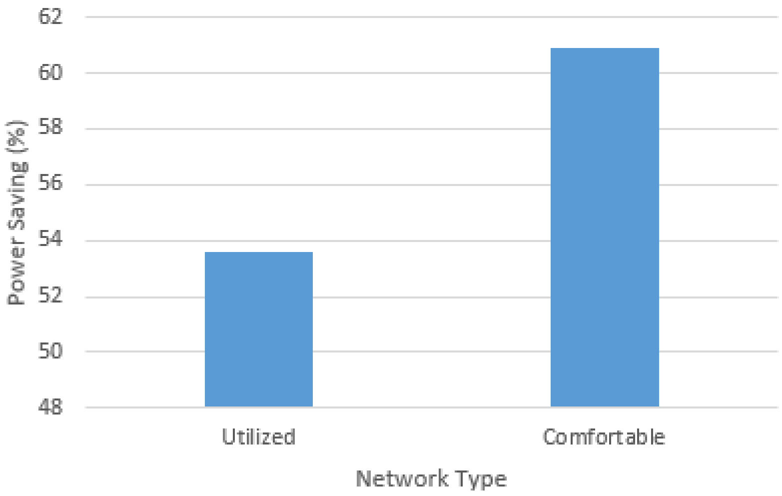


FIGURE 4.4: Power Saving vs. Network Type

More comfortable network planning results in more power saving potential as displayed in Figure 4.4. This makes sense as in comfortable network planning there is more spare resources available and not utilized for the same number of users compared with utilized planning.

4.2.3 Experiment 3: Load Factor Impact

Different daily load demand levels result in different behaviors in response to power saving algorithm, with fixing the following simulation parameters, the impact of LF variation on power saving is tested:

- Node selection method is Minimum Weighted Degree Centrality.
- Number of MBSs is 100 nodes.
- Total number of nodes is 2000 nodes.
- Network type is Utilized Network.
- $\alpha = 24$ (worst case value, more details on section 3.2)

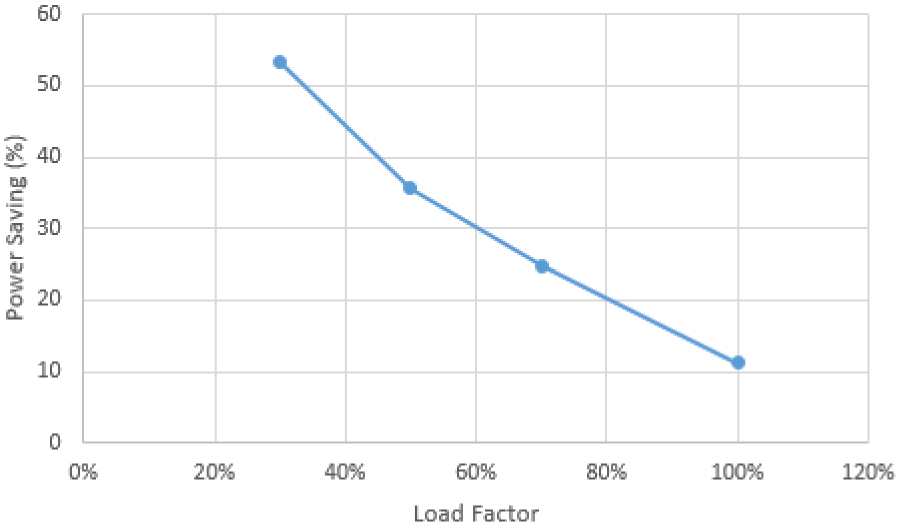


FIGURE 4.5: Power Saving vs. Load Factor

Variation in network traffic demands during the day directly impacts saving ratio as what Figure 4.5 obviously tells, this means at low traffic times more savings can be achieved. Load variation happen in daily, weekly, and monthly basis according to network traffic profile during the year.

4.2.4 Experiment 4: Dynamic Power Compensation

Different distance levels of UEs from MBSs result in different behaviors in response to power saving algorithm, with fixing the following simulation parameters, the variation impact of α value on **STAR5** is tested:

- Node selection method is Minimum Weighted Degree Centrality.
- Number of MBSs is 100 nodes.
- Total number of nodes is 2000 nodes.
- Network type is Utilized Network.
- Off- Peak traffic profile.

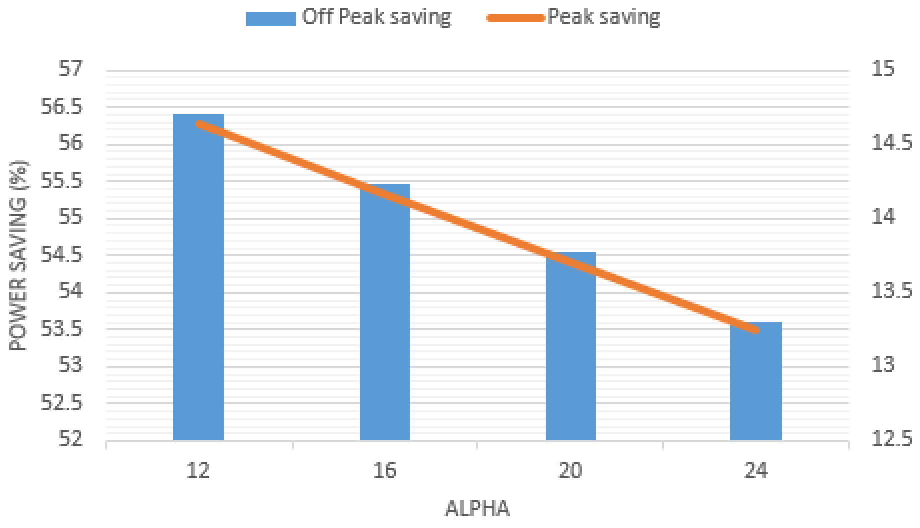


FIGURE 4.6: Power Saving vs. Alpha Value

As the value of α increases, the power saving ratio slightly decreases as shown in Figure 4.6. This variation comes from the required dynamic power compensation to re-allocate traffic from SCs to MBSs (please refer to Section 3.2 for more details).

4.2.5 Experiment 5: BS Selection Method

As discussed earlier, the proposed power saving algorithm is applied in a random or specific order of selected nodes to put in power saving mode. However, the maximum power saving depends on BSs selection order. In this experiment, different node selection methods that are used as input to the power saving algorithm are tested, with fixing the following simulation parameters:

- Total number of nodes is 2000 nodes.
- Number of MBSs is 100 nodes.
- Network type is Utilized Network.
- Off- Peak traffic profile.
- $\alpha = 24$ (worst case value, more details on section 3.2)

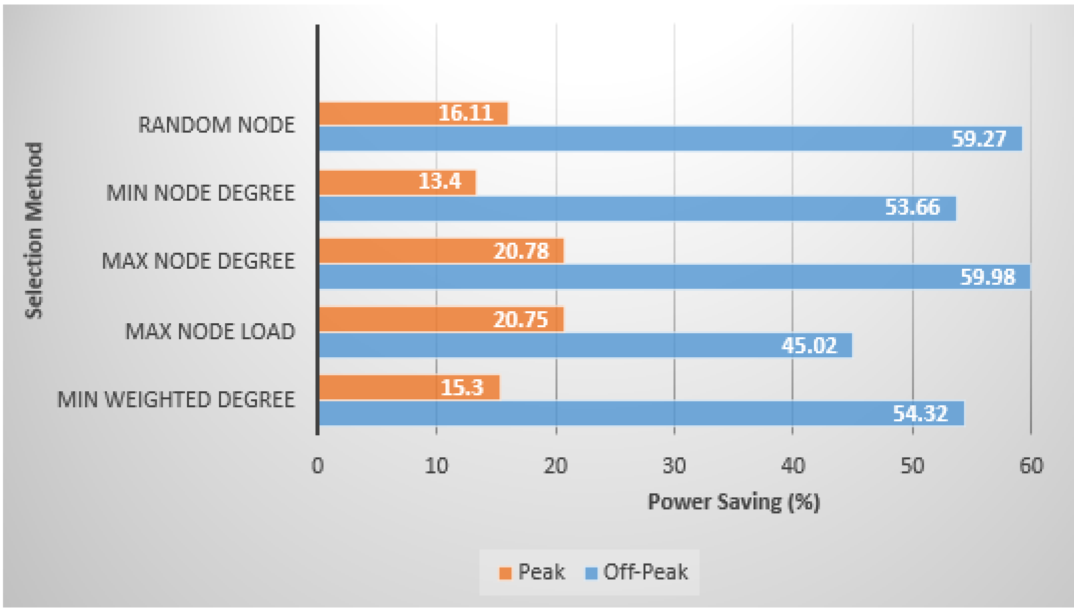


FIGURE 4.7: Power Saving vs. Node Selection Method

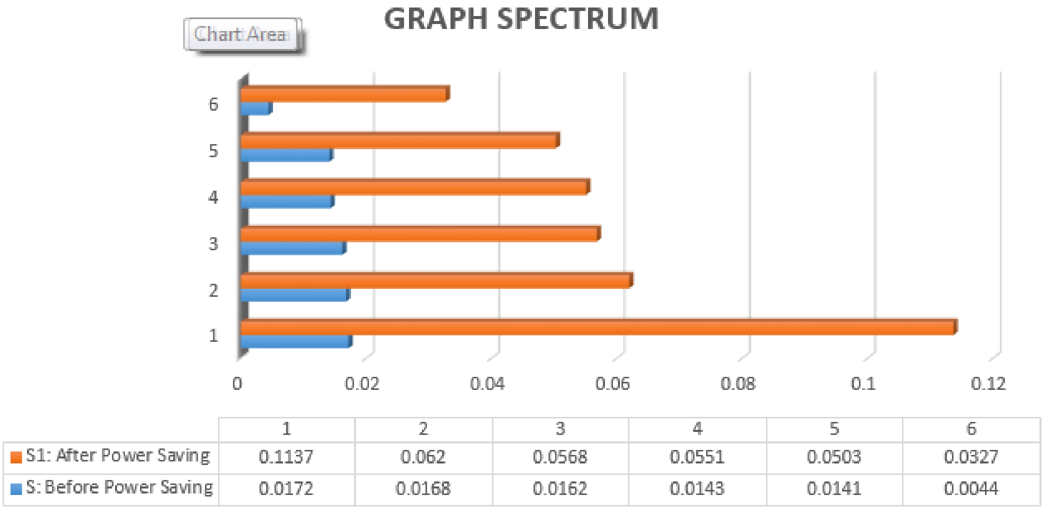
Most of the tested methods are performing good in general as concluded from Figure 4.7, but Maximum Node Degree Centrality method is the one which gives the maximum power saving at both peak and off-peak time. From results analysis **STAR5** outperforms the results of the best in class optimization algorithms mentioned in related work, our algorithm was able to achieve 60% in off-peak time and 21% in peak time while satisfying desgin constraints.

4.2.6 Experiment 6: Network Connectivity

Network connectivity verification using algebraic connectivity tests is performed on graph H before power saving and graph $H1$ after power saving, the following simulation parameters used to generate graph H and to run power saving algorithm:

- Total number of nodes is 2000 nodes.
- Number of MBSs is 100 nodes.
- Network type is Utilized Network.
- Node selection method is Maximum Node Degree Centrality.
- $\alpha = 24$ (worst case value, more details on section 3.2)

Figure 4.8 presents the first six values of graph's Laplacian matrix eigenvalues (Graph Spectrum), as the Algebraic Connectivity represented in the second eigenvalue is > 0, we conclude that the graphs (before power saving 'H', and after power saving 'H1') are connected graphs.



	1	2	3	4	5	6
🟧 S1: After Power Saving	0.1137	0.062	0.0568	0.0551	0.0503	0.0327
🟦 S: Before Power Saving	0.0172	0.0168	0.0162	0.0143	0.0141	0.0044

FIGURE 4.8: Graph Eigenvalues Before and After Power Saving

The algebraic connectivity is shown in Figure 4.9, the more the value of algebraic connectivity the more the stability and robustness of graph. The algebraic connectivity of the modeled network is greater than zero before and after power saving, which means network connectivity is guaranteed according to design constraints. Moreover, the algebraic connectivity increased after power saving, this is an explained behavior because network size decreased and layout became more robust with smaller network nodes distribution and more compact layout as plotted in Figure 4.10 [18].

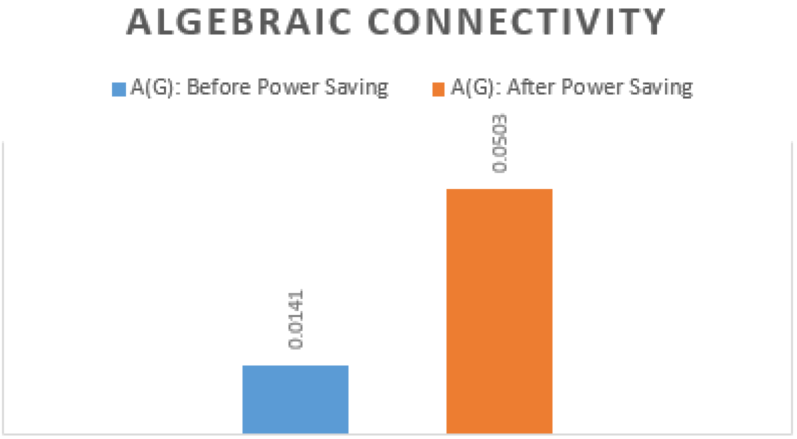


FIGURE 4.9: Algebraic Connectivity Before and After Power Saving

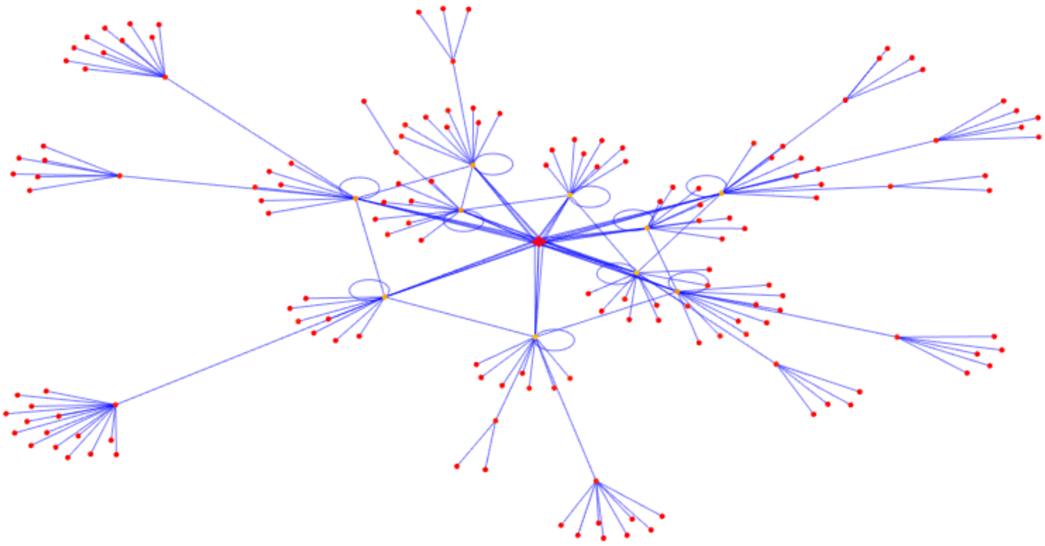


FIGURE 4.10: Network Layout after Power Saving

4.3 Discussion

From simulation results, we conclude that **STAR5** is performing well in different network conditions, and it is robust against the different methods used to run this algorithm.

NEO is dynamic and scalable, which gives the flexibility to optimize radio network parameters according to the desired network size, BS utilization, traffic conditions, BSs density, distance between UE and BS represented by α and β factors, maximum capacity and power consumption for the cell, and many other optimization parameters.

STAR5 is considering saving from both types of radio nodes in this model: MBSs, and SCs. It saves static power in MBSs as it is a major contributor in power consumption from specifications. in SCs the algorithm saves static power on both SC and its connecting Edges provided that utilization constraints are not violated.

STAR5 is taking into consideration the compensation in dynamic power when re-allocating SC's traffic to MBS to compensate for the increased transmission power requirements due to increased distances between UE and new MBS. This compensation can result in negative savings in dynamic power but the total result including static power is positive saving.

STAR5 guarantees that nodes with utilization exceeds 70% should not be put in sleep mode. On the contrary, if a node when checked during power saving process found with utilization exceeding 90%, the power-on algorithm tries to help it by activating nearest nodes if any were in sleep mode "Fairness Problem" according to what has been described in power-on algorithm description. This results in non of the BSs has utilization exceeding its capacity limitation after power saving as plotted in Figure 4.11.

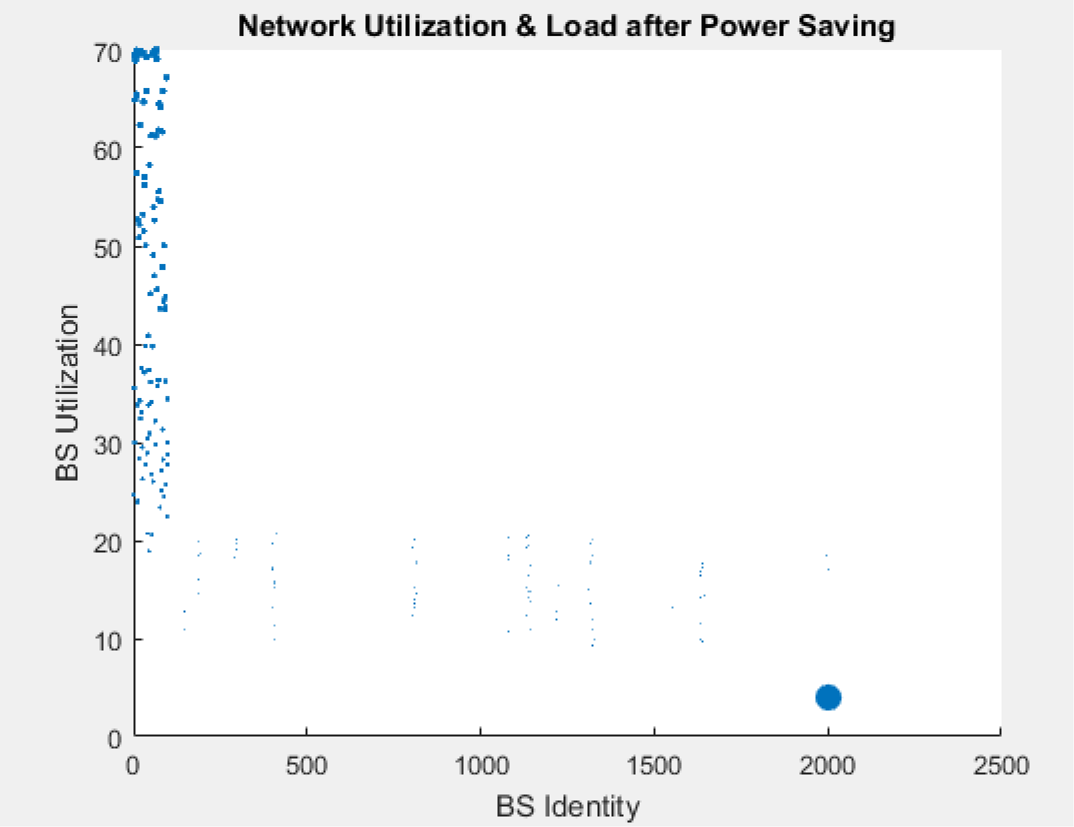


FIGURE 4.11: Network Utilization and Load After Power Saving. Y-axis represents base station utilization, nodes' size represents base station traffic volume.

Network layout after power saving is shown previously in Figure 4.10, SCs put in power saving mode are removed from graph with their edges. However, MBSs are kept in the graph because they are put partially in power saving mode with a minimum guaranteed capacity of 30%.

STAR5 shows high efficiency, it was able to achieve up to 20% power saving in peak traffic time, and up to 60% in off-peak time. Detailed power saving (dynamic and static) in watt from both nodes and links is summarized in Figure 4.12. Saving in off-peak compared to peak time is represented in Figure 4.13.

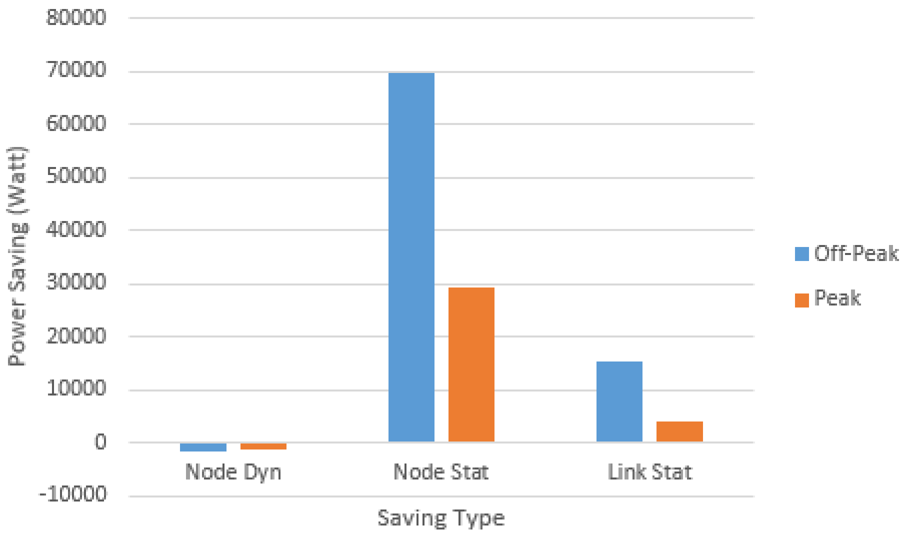


FIGURE 4.12: Detailed Power Saving using Max. Degree Method

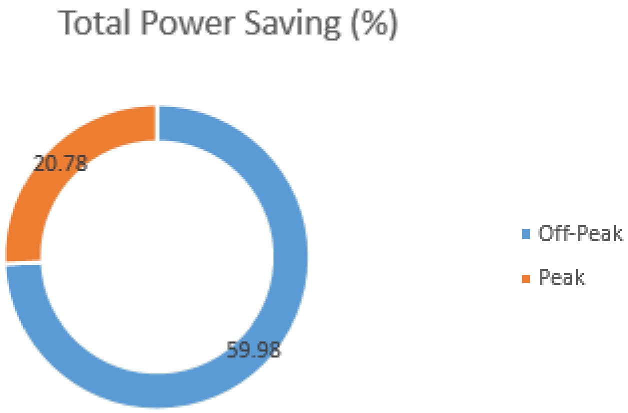


FIGURE 4.13: Saving Percentage using Max. Degree Method

Beside their efficiency, **NEO** and **STAR5** are robust and satisfy the design constraints. One of the important constraints is network connectivity. Network connectivity through algebraic connectivity was discussed in section 4.2.6. The network is guaranteed connected and then no coverage-holes are expected or allowed. Putting BSs in power saving mode didn't impact the network connectivity, it made network more robust which is reflected in the increased value of algebraic connectivity.

As **STAR5** is able to put huge number of SCs in power saving mode depending on traffic demand, frequency recycling from SCs put in power saving mode is possible to other SCs which have growing traffic or to increase the available bandwidth on target cells. This thesis work doesn't go deep in frequency planning and assignment, this part is left to the available frequency planning tools and for future improvements on **STAR5**.

STAR5 works on a centralized machine connected to mobile network and fed by statistical reports in periodic intervals. The algorithm runs each time it receives updated input from network. As this is a centralized method the computational time plays important role so that the results of the power saving algorithm should be close to real time and the output should reflect the realistic network status. The complexity of the code $O(f(N))$ is $O(n)$ where $f(N)$ is a linear function. The size of input can be the number of non-zero elements in incidence matrix, the number of vertices or the number of edges or some combination of both [15].

Chapter 5

Conclusions and Perspectives

The main part of this thesis proposed a novel algorithm to improve energy efficiency in ultra-dense future 5G networks. The algorithm designed for multi-layer radio network and works in cooperative way between radio layers. Cellular network was modeled as a graph to simplify algorithm complexity, the graph connectivity is an important measure for network radio coverage continuity.

In the last years, the issue of energy efficiency has become one of the main concerns for both the industries and research community, because of its promising economical benefits and of its expected environmental impact.

5.1 Conclusions

This thesis discussed the demands and expectations from next generation 5G networks such as higher data rates, reduced latency for critical applications, reduced power consumption in network and handsets, and the improved security and QoS. The key drivers for researchers towards 5G evolution is the foretasted exponential rise in Smart Phones and mobile broadband usage coming from growing number of subscribers and IoT applications, beside the increased usage of internet applications and social media. 5G RAN will be an integrated technology of evolved multiple cooperating RATs.

Furthermore, 5G networks will consist of multiple tiers of heterogeneous networks (HetNets). The architecture of the 5G RAN systems will consist of MBSs and SCs (i.e. micro cell, pico cell, femto cell, relay and device to device (D2D)) based communication tiers, each could be of different RATs. Marco cells are used in rural and suburban areas, integrated SCs are used in urban and dense urban areas. In dense urban areas ultra-dense SCs are considered a key enabler for 5G, with this expected densification the importance of energy saving in UDN networks rises. This thesis considered a cooperative energy saving approach between MBS and SC layers beside the saving achieved from backbone network.

Thesis work also discussed the increased interest of using graph theory in dealing with mobile networks. As 5G networks are expected to be multi-layer, multi-RAT, ultra-dense networks, this makes dealing with such complex networks using previous methods a hard problem. To simplify the problem, 5G network was modeled using graph theory, analysis was done on a sample model of randomly generated 2000 nodes making a weighted and un-directed graph, the weight represents traffic flow over backbone network. Network model is of multi-layers consisting of

Aggregation nodes, MBSs, and SCs. Graph theory usage simplified problem complexity to linear equation, and enabled the usage of graph properties to optimize network and investigate its properties such as centrality measures and algebraic connectivity.

There were several simulation parameters considered in the experiments performed to validate algorithm efficiency and effectiveness. The algorithm was run using different node selection methods in its iterations. Maximum node degree method showed the best performance in both peak and off-peak hours. Results also showed more saving in comfortable network designs than more utilized networks. Saving is inversely proportional to LF; the increase in hourly load implies a decrease in power saving percentage. The value of α which represents the relation between dynamic power consumption and UE distance from BS's antenna can slightly impact power saving ratio in such UDN environment. The ratio of SCs and MBSs, together with network size impact the achieved power saving. It is noted that most of static power consumption is coming from the MBSs which transmit over large areas and apply advanced radio technologies such as MIMO, thus 5G requires advancement in MBS design to reduce its power consumption. Network connectivity and robustness was measured and guaranteed using algebraic connectivity. The proposed algorithm was able to achieve savings up to 60% in off-peak hours and 21% in peak time.

In a nutshell, results showed robust and efficient algorithm design with power saving ratio up to 60% during off-peak time. Algorithm guarantees design constraints which are network connectivity and coverage-hole avoidance, subscriber perceived QoS and data rates, and BSs capacity limits.

5.2 Perspectives

The work in this thesis can be extended in future to include the following research topics, which were not covered in this thesis due to lack of time:

- **Frequency Recycling**
  Frequency recycling could be achieved after power saving in SCs, once SC put in power saving mode its frequency carrier can be recycled to a neighbor SC to increase data rate, this part is kept for future work and can be done currently using available frequency planning tools.

  The designed model is considering radio network without frequency carrier allocation, these are kept dummy values as the link weight which represents traffic flow is the important measure to optimize cell's utilization and network power consumption.

- **Femto Cells and Remote Radio Head (RRH)**
  Femto cells are considered as low cost low power cells and can operate under licensed/unlicensed spectrum, they can be managed by operator/users, such type of cells will be of very huge numbers and can complicate optimization

process as number of nodes N becomes very high, it can be considered in later releases.

Algorithm considers only MBS and SC Base station types. The RRH and Base Band units are being discussed in literature, but for simplicity this type of radio components is left for future work.

- **Localization**
  Design algorithm takes care of network size and cells distribution among clusters of MBSs and SCs; however, distances and physical localization is not part of the design, localization can help broaden code usage for other projects simulation purposes and can be considered for later work.

It is our hope that the findings in this thesis may help to a better understanding of Energy Efficiency in 5G UDNs while stimulating further work in this area.

Bibliography

[1] Ericsson AB, “Ericsson Mobility report, Power Point Presentation," Retrieved from URL "https://www.ericsson.com/en/mobility-report" on November, 2016.

[2] Nokia report, “Ten key rules of 5G deployment.” Retrieved from URL "https://resources.ext.nokia.com/asset/200006" on November, 2016.

[3] Ericsson AB, “Thinking across the generations: Radio Network Evolution on the road to 5G," Power Point Presentation, 2016.

[4] Tutorial 5: Small-cells: Capacity, Mobility and Energy Efficiency Perspectives’, IEE International Conference on Communications, IEEE ICC2014, Sydney Australia, http://icc2014.ieee-icc.org, 10 June 2014.

[5] Olwal, Thomas O., Karim Djouani, and Anish M. Kurien. "A survey of resource management toward 5G radio access networks."IEEE Communications Surveys and Tutorials, 1656-1686, 2016.

[6] Chuang, Ming-Chin, Meng Chang Chen, and S. Yeali. "Resource management issues in 5G ultra dense smallcell networks." Information Networking (ICOIN), 2015 International Conference on. IEEE, 2015.

[7] Q. Li, G. Li, W. Lee, M. Lee, D. Mazzarese, B. Clerckx, and Z. Li, “MIMO Techniques in WiMAX and LTE: A Feature Overview,” IEEE Communications Magazine, vol.48, no.5, pp.86-92, May 2010.

[8] 3GPP, TS 36.300, “Evolved Universal Terrestrial Radio Access (EUTRA) and Evolved Universal Terrestrial Radio Access Network (EUTRAN); Overall description; Stage 2,” v12.2.0, June 2014.

[9] 3GPP, TS 36.211, “Evolved Universal Terrestrial Radio Access (EUTRA); Physical channels and modulation,” v12.2.0, July 2014.

[10] Y. Wang, K. Pedersen, P. Mogensen, and T. Sorensen, “Carrier Load Balancing Methods with Bursty Traffic for LTE-Advanced Systems,” IEEE PIMRC, pp. 22-26, September 2009.

[11] Outlook-Wireless World Research Forum, "Outlook16.pdf," Retrieved from URL "http://www.wwrf.ch/files/wwrf/content/files/publications/outlook/Outlook16.pdf" on May, 2017.

[12] M. Pejanovic-Djurisic, E. Stovrag and M. Ilic-Delibasic, “Fundamental Optimization Criteria For Green Wireless Communications,” MIPRO, 2012 Proceedings of the 35th International Convention, pp. 733-736, May 2012.

[13] A. Amokrane, R. Langar, R. Boutaba, and G. Pujolle, “A Green Framework for Energy Efficient Management in TDMA-based Wireless Mesh Networks,” 2012 8th International Conference and 2012 Workshop on Systems Virtualiztion Management (SVM), pp. 322-328, October 2012.

[14] Chiaraviglio, Luca, Marco Mellia, and Fabio Neri."Reducing power consumption in backbone networks." Communications, 2009. ICC'09. IEEE International Conference on. IEEE, 2009.

[15] Keijo Ruohonen. GRAPH THEORY Book. Springer Science and Business Media, pp. 50-51, 2013.

[16] M. Fiedler, "Algebraic connectivity of graphs," Czechoslovak mathematical journal, vol. 23, no. 2, pp. 298–305, 1973.

[17] MATLAB and Statistics Toolbox Release 2012b, The MathWorks, Inc., Natick, Massachusetts, United States.

[18] A. Jamakovic and S. Uhlig, "On the relationship between the algebraic connectivity and graph's robustness to node and link failures," in Next Generation Internet Networks, 3rd EuroNGI Conference on. IEEE, pp. 96–102, 2007.

[19] K. Son, H. Kim, Yung Yi, and B. Krishnamachari, "Base Station Operation and User Association Mechanisms for Energy-Delay Tradeoffs in Green Cellular Networks," IEEE Journal on Selected Areas in Communications, vol. 29, no. 8, pp. 1525-1536, 2011.

[20] Z. Hasan, H. Boostanimehr, and V.K. Bhargava, "Green cellular networks: A survey, some research issues and challenges," IEEE Commun. Surveys Tuts., vol.13, no.4, pp.524-540, Fourth Quarter 2011.

[21] H. Bogucka and A. Conti, "Degrees of Freedom for Energy Savings in Practical Adaptive Wireless Systems," IEEE Communications Magazine, vol. 49, no. 6, pp. 38-45, 2011.

[22] Osseiran, Afif, et al. "Scenarios for 5G mobile and wireless communications, the vision of the METIS project." IEEE Communications Magazine, pp. 26-35, 2014.

[23] Yu, Wei, et al. "Towards energy efficiency in ultra dense networks." Performance Computing and Communications Conference (IPCCC), 2016 IEEE 35th International. IEEE, 2016.

[24] Ruuska, Tauno. "Adaptive power management for a node of a cellular telecommunications network." U.S. Patent No. 6,584,330. 24 Jun. 2003.

[25] Lin, Murong, Quanmin Ye, and Yinghua Ye. "Graph theory based mobile network insight analysis framework." Ubiquitous Computing, Electronics and Mobile Communication Conference (UEMCON), IEEE Annual. IEEE, 2016.

[26] Bello Orgaz, Gema, Jason J. Jung, and David Camacho. "Social big data: Recent achievements and new challenges." Information Fusion 28, pp.45-59, 2016.

[27] Smallcell forum, Retrieved from URL "http://www.smallcellforum.org/ " on June, 2017.

[28] V. Chandrasekhar, J. G. Andrews, and Alan Gatherer, "Femtocell networks: a survey," IEEE Communication Magazine, vol. 46, no. 9, pp. 59-67, September 2008.

[29] Mwanje, Stephen, et al. "Network management automation in 5G: Challenges and opportunities." Personal, Indoor, and Mobile Radio Communications (PIMRC), 2016 IEEE 27th Annual International Symposium on. IEEE, 2016.

[30] D. Lopez-Perez, G. de la Roche, A. Valcarce, A. Juttner, and J. Zhang, “Interference avoidance and dynamic frequency planning for WiMAX femtocells networks,” IEEE International Conf. on Commun. Systems, pp. 1579-1584, Nov 2008.

[31] S. Parkvall, A. Furuskar, E. Dahlman, “Evolution of LTE toward IMTadvanced,” IEEE Communications Magazine, vol. 49, pp. 84-91, Feb. 2011.

[32] A. Ghosh, R. Ratasuk, B. Mondal, N. Mangalvedhe, and T. Thomas, “LTE-advanced next-generation wireless broadband technology,” IEEE Wireless Communications, vol. 17, pp. 10-22, Jun. 2010.

[33] David Gesbert and Marios Kountouris, “Rate Scaling Laws in Multicell Networks Under Distributed Power Control and User Scheduling,” IEEE Trans. on Information Theory, vol. 57, no. 1, pp. 234-244, Jan. 2011.

[34] V. Chandrasekhar, J. G. Andrews, T. Muharemovic, and A. Gatherer, “Power Control in Two-Tier Femtocell Networks,” IEEE Trans. On Wireless Communications, vol. 8, no. 8, pp. 4316-4328, Aug. 2009.

[35] A. Bousia, E. Kartsakli, L. Alonso and C. Verikoukis, “Dynamic Energy Efficient Distance-Aware Station Switch On-Off Scheme for LTEAdvanced,” IEEE GLOBECOM, pp. 1532-1537, December 2012.

[36] O. H. Eunsung, S. Kyuho and B. Krishnamachari, “Dynamic Base Station Switching-On Off Strategies for Green Cellular Networks,” IEEE Transactions on Wireless Communications, vol. 12, no. 5, pp. 2126- 2136, May 2013.

[37] Chen-Yi Chang, Wanjiun Liao, Hung-Yun Hsieh, and Da-shan Shiu, “On Optimal Cell Activation for Coverage Preservation in Green Cellular Networks,” IEEE Transactions on Mobile Computing, vol. 13, no. 11, pp. 2580-2591, November 2014.

[38] Meskar, Erfan, et al, "Energy Aware Offloading for Competing Users on a Shared Communication Channel." IEEE Transactions on Mobile Computing, vol. 16.1, pp. 87-96, 2017.

[39] Wu, Yuan, et al. "Energy-aware cooperative traffic offloading via devicetodevice cooperations: an analytical approach." IEEE Transactions on Mobile Computing vol. 16.1 ,pp. 97-114, 2017.

[40] Arani, Atefeh Hajijamali, et al. "Learning-based joint power and channel assignment for hyper dense 5G networks." Communications (ICC), 2016 IEEE International Conference on. IEEE, 2016.

[41] Ge, Xiaohu, et al. "Energy Efficiency Challenges of 5G Small Cell Networks." arXiv preprint arXiv:1702.03503, 2017.

[42] Auer, Gunther, et al. "How much energy is needed to run a wireless network?." IEEE Wireless Communications 18.5 (2011).

[43] 3GPP TR 36.814 v9.0.0, “Further advancements for E-UTRA. Physical layer aspects (Release 9),” 3GPP, Technical Specification Group Radio Access Network, Mar. 2010.

[44] Saad, Sawsan A., Mahamod Ismail, and Rosdiadee Nordin. "A survey on power control techniques in femtocell networks." JCM 8.12 , pp. 845-854, 2013