4G-LTE WITH NS-3 SIMULATION

A report
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in the **Electrical communication Engineering**

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Abstract

4G refers to the fourth generation of cellular wireless standards. It is a successor to 3G and 2G families of standards.

The predecessors of 4G are LTE, WIMAX, UMB AND Flash-OFDM. OFDM is designed to send data over hundreds of parallel streams, thus increasing the amount of information that can be sent at a time over traditional CDMA networks.

4G supports IPV6 for faster internet access. There is a deep history for 4G technology evolution. 4G is a collection of wireless standards. The IEEE has standardized 4G as 802.16m.

The goal of 4G systems such as high rate, high reliability, and long range communications has increased its use and the evolution. The fourth generation of mobile networks will truly turn the current mobile phone networks, in to end to end IP based networks. 4G is set to deliver 100mbps to a roaming mobile device globally, and up to 1gbps to a stationary device.

Currently 3G networks still send their data digitally over a single channel. The 4G is largely implemented outside India and will be soon adopted by Indian cellular companies. Beyond 4G the world has also seen the concept of 5G.

Here I try to understand the basic structure of the 4G with the architecture of 4G in different scenarios . I also try to understand the architecture of LTE which includes EPC model and E-UTRAN model and working of the LTE model. I also understand that how resource is allocated in the 4G with the Qos parameters and scheduling process in LTE . I also use Network Simulator for the simulation 4G and trace the output.

I also make a survey to the ECE labs and CDS and get the information about the research works done in labs.

Contents

1 Introduction

4G is the fourth generation of broadband cellular network technology, succeeding 3G. A 4G system must provide capabilities defined by ITU in IMT Advanced. Potential and current applications include amended mobile web access, IP telephony, gaming services, high-definition mobile TV, video conferencing, and 3D television.

The first-release Long Term Evolution (LTE) standard was commercially deployed in Oslo, Norway, and Stockholm, Sweden in 2009, and has since been deployed throughout most parts of the world. It has, however, been debated whether first-release versions should be considered 4G LTE.

Old-school 1G (first-generation) networks, built in the 1980s, were analog, and they carried only voice calls. In the early 1990s, digital 2G (second-generation) began their ascent, allowing for basic data services such as text messaging and email.

3G networks began spreading in the early 2000s, and with them, so too did the concept of mobile Internet. With a fast connection, you could surf the Web, play streaming audio, although the experience was sometimes obscenity-spewing slow.

Then consumers began clamoring for even more fabulous, Web-centric mobile capabilities. Mobile devices with advanced and data-hungry capabilities exploded in numbers. In the meantime, network infrastructures began creaking under the weight of immense demands for data. 3G needed more oomph. It was time for wireless networks to evolve once again, this time to provide speedier mobile broadband service. That time is now.

Like 3G, 4G networks are IP-based (Internet protocol), meaning that it uses a standard communications protocol to send and receive data in packets. Unlike 3G, however, 4G uses IP even for voice data. It is an all-IP standard. These days, network generational lines are a little more confusing. There's no universally recognized standard for 4G.
So, faster-than-3G systems are often referred to as 3.5G or 3.9G, or simply 3G+. However, marketing campaigns from major carriers, who are always looking for a competitive edge, refer to these networks as 4G. In short, 4G is merely a marketing term. It means only that a network is faster than 3G. That's it

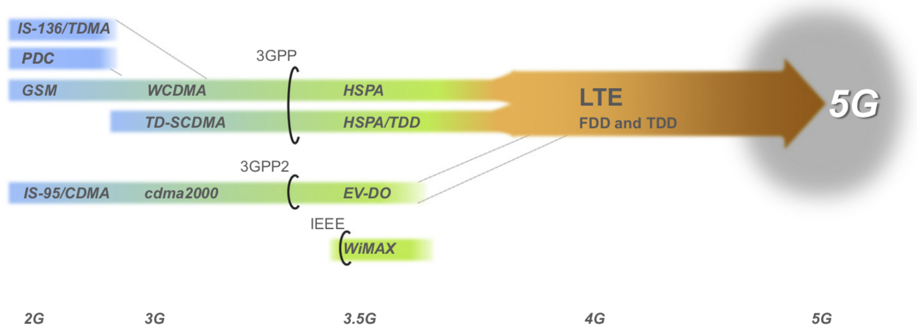


Figure 1: **Evolution of 4G**

1.1 Properties of 4G Network

- 4G has **higher capacity**, meaning it can support a greater number of users at any given time. It sports higher data rates, so that multimedia applications such as video calling or YouTube clips work more smoothly. With a 3G tower, about 60 to 100 people can share the signal and get fast, reliable service. A 4G LTE (Long Term Evolution) tower, however, can serve around 300 or 400 people.

- 4G has **reduced latency** , A network that qualifies as real-time speed has a latency of 50ms (milliseconds) or less; 4G LTE has a **latency** of only around 20 to 40ms. Low latency also means voice calls don't have any lag or echo, echo, echo.

- 4G is more **spectrally efficient** than 3G. Think of radio spectrum as a pipe of a certain diameter; only so much data can go through that pipe at one time. But 4G uses clever coding schemes to dramatically increase the amount of data that rushes through the spectrum. Ultimately, it delivers more bits per hertz than 3G.

- In this situation, 3G systems balk and stumble, leaving users frustrated. The more sophisticated, **self-organizing** and **self-configuring**

4G systems, however, can compensate on the fly and provide faster service for more people. Similarly, power outages and equipment failures often cripple 3G systems. But thanks to sensors and advanced software, a 4G system has self-healing capabilities that let it route traffic through other towers until repairs are made.

- 4G networks assign far **spectrum** for receiving, and as result, achieve better overall speed.

- The **4G cell radius** will, in general, most likely be smaller because the propagation loss is increased by operating at higher frequencies and at higher transmission bit rates the received signal level threshold must be higher than at lower bit rates, in order to compensate for the greater affect of noise at higher bit rates i.e to receive the signal at an adequate SNR (Signal to Noise Ratio). The Equations that govern cell size:
  Lp = 38 * log(d) + 21 * log(f) + c
  dLb = 10 * log(B/B0)
  Rr = 1/10 ˆ((21 * log(f/f0) + 10 * log(B/B0)) / 38)

  Where:
  Lp = Propagation Loss
  d = Distance
  f = frequency
  c = constant, dLb = Increase in noise power
  B = Bit rate
  B0 = Reference Bit Rate
  Rr = Relative Cell Radius
  f0 = Reference frequency

2 4G Applications in various fields

2.1 Narrow-Band-IoT

NB-IoT or NB-LTE is a new 3GPP radio-access technology. It is not fully backward compatible with existing 3GPP devices however it is designed to achieve excellent co-existence performance with legacy GSM, GPRS and LTE technologies. NB-LTE requires 200 kHz minimum system bandwidth for both downlink and uplink, respectively. The choice of minimum system bandwidth enables a number of deployment options like a GSM operator can replace one GSM carrier (200 kHz) with NB-IoT or a LTE operator can deploy NB-LTE inside an LTE carrier by allocating one of the Physical Resource Blocks (PRB) of 180 kHz to it.

NB-IoT reuses the conventional LTE design extensively, including the numerologies, downlink OFDMA, uplink SC-FDMA, channel coding, rate matching, interleaving, etc. This significantly helps to reduce the time required to develop full design specifications. Also, it is expected that the time required for developing NB-IoT products will be significantly reduced for existing LTE OEMs and ODMs.

NB-LTE also use the same Networks architecture as of conventional LTE Network with some optimization required to support IoT Massive user requirements. The basic architecture for NB-LTE is shown in below and similar to LTE network consist of two part namely Access Network and Evolved Packet System (EPS) Core Network. In access network architecture there is no change, but at Core network the both user plane and control plane, some other optimizations are done to support IoT application. A new node has been introduced as SCEF (Service Capability Exposure Function). The SCEF is designed especially for machine type data. It is used for delivery of non-IP data over control plane and provides an interface for the network services (authentication and authorization, discovery and access network capabilities).

A list of common optimizations required for IoT support at EPS are listed below:

- On the Control Plane, UL data can be transferred from the eNB to the MME. From there, it may either be transferred via the Serving Gateway (SGW) to the Packet Data Network Gateway (PGW), or to the Service Capability Exposure Function (SCEF) which however is only possible for non-IP data packets. From these nodes, they are finally forwarded to the application server or IoT Services. The same

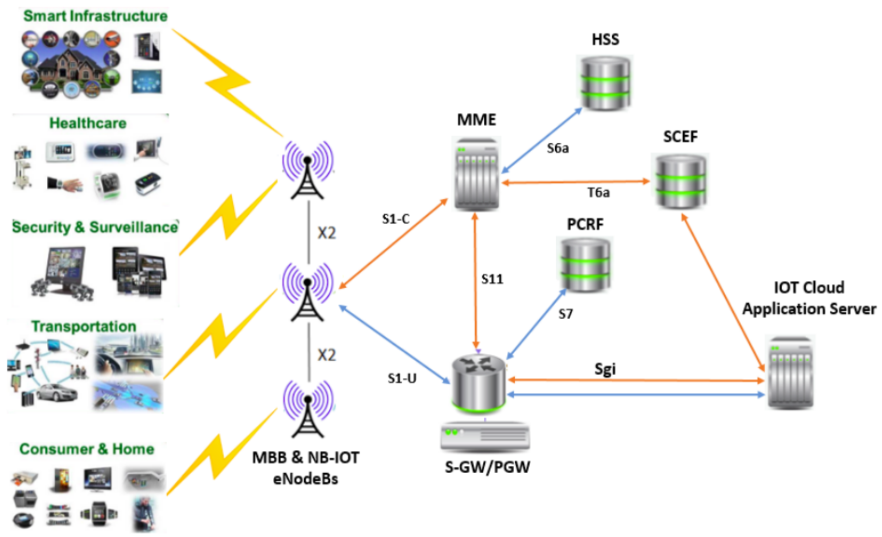


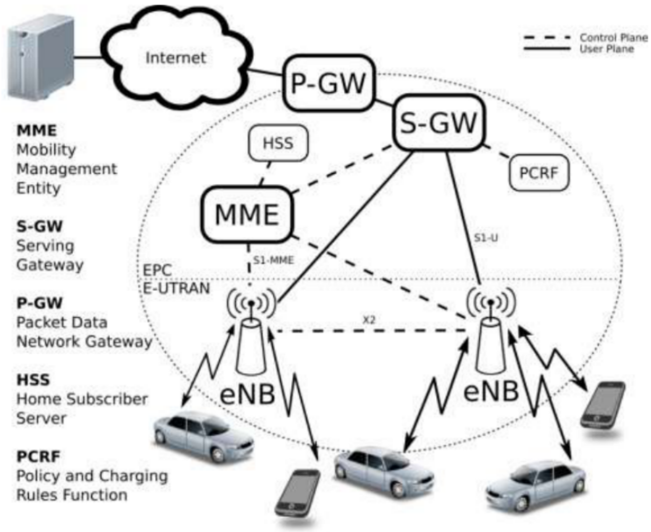
Figure 2: NB-IoT Architecture

is depicted by Orange line. DL data is transmitted over the same paths in the reverse direction. This approach does not require radio bearers, data packets can be sent on the signaling radio bearer instead. Consequently, this solution is most appropriate for the transmission of infrequent and small data packets.

- With the User Plane EPS optimization, data is transferred in the same way as the conventional data traffic, i.e. over radio bearers via the SGW and the PGW to the application server. Thus, it creates some overhead on building up the radio bearer connection, however it facilitates a sequence of data packets to be sent. This approach requires supports delivery of both, IP and non-IP data packets with EPS.
- Another possible optimization can be done for reducing signaling by guiding IoT devices to perform periodic location updates less frequently and by optimizing paging. Reducing signaling can help avoiding overload situations in massive device network.

2.2 Vehicular Networking :

LTE is the most promising wireless broadband technology that provides high data rate and low- latency to mobile users. Like all cellular systems, it can benefit from a large coverage area, high penetration rate, and high-speed ter-



minal support. Extending its use also to support vehicular applications would open new market opportunities to Telco operators and service providers. Vehicles are indeed the third place, after home and office, where citizens spend more time daily.

Indeed, LTE particularly fits the high-bandwidth demands and QoS-sensitive requirements of a category of vehicular applications, known as infotainment (information and entertainment), which includes traditional and emerging Internet applications (e.g., content download, media streaming, VoIP, web browsing, social networking, blog uploading, gaming, cloud access).

The main concern comes from the centralized LTE architecture: communications always cross infrastructure nodes, even though all that is required is a localized V2V data exchange, as for safety-critical applications, with negative consequences on the message latency. In addition, in dense traffic areas, the heavy load generated by periodic message transmissions from several vehicles, strongly challenges the LTE capacity and potentially penalizes the delivery of traditional applications.

Active road safety applications aim at reducing the risk of car accidents and have timeliness and reliability as the major requirements. Two main types of safety messages have been standardized whose transmissions can be periodic or event-triggered. In ETSI documents [16] they are respectively referred to as Cooperative Awareness messages (CAMs) and Decentralized Environmental Notification Messages (DENMs); Basic Safety Messages (BSMs) is instead the terminology used in for both periodic and event-triggered messages.

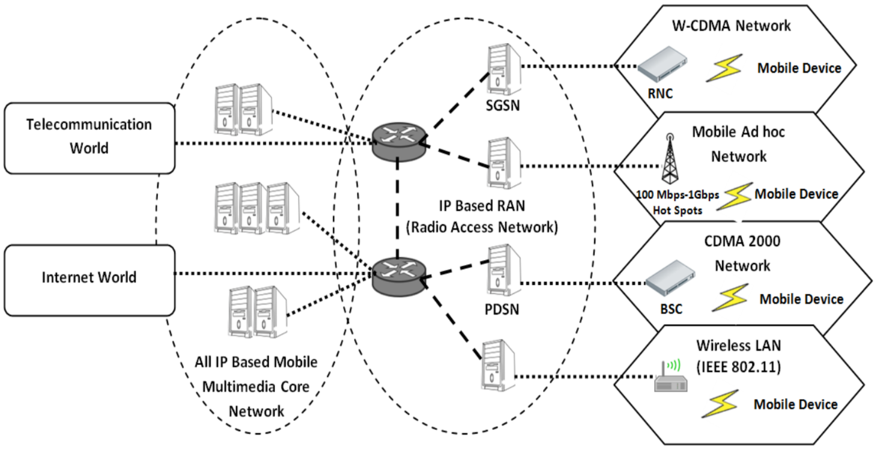
LTE can provide a Round Trip Time theoretically lower than 10 ms, and transfer latency in the radio access up to 100 ms. This is especially beneficial for delay-sensitive vehicular applications. The access network is composed of eNodeBs, which manage radio resources and handover events, whereas the core network is composed of three main units: the MME, responsible or control procedures, such as authentication and security, and storing information; the S-GW, responsible for routing, data forwarding, and charging by coupling with the PCRF; the P-GW, the outgoing entity which allows communication with IP and circuit-switched networks.

2.3 Cellular Network :

Long Term Evolution (LTE) is a 4G wireless broadband technology developed by the Third Generation Partnership Project (3GPP), an industry trade group.The LTE technology enabled fast mobile internet connection. Actually, LTE is a path followed to achieve 4G speeds. LTE is a full IP technology used for the mobile broadband services for data transfer and voice calls. Soon it will be used for the Multimedia Broadcast Multicast Service (MBMS). Wireless operators are rapidly expanding their LTE networks to take advantage of additional efficiency, lower latency and the ability to handle ever-increasing data traffic. The core technologies have moved from circuit-switching to the all-IP evolved packet core. Meanwhile, access has evolved from TDMA (Time Division Multiple Access) to OFDMA (Orthogonal Frequency Division Multiple Access) as the need for higher data speeds and volumes as increased. LTE network architecture cab be divided into two sub networks.

Radio Access Network for LTE : The radio access network is used for wireless radio connection between the mobile phones and antennas from the mobile operator. The radio access network is also called EUTRAN or Evolved Universal Mobile Telecommunications System Terrestrial Radio Access Network. EUTRAN can be also called just LTE (Long Term Evolution). Radio infrastructure is formed of the following nodes:

LTE Mobile Terminals: LTE mobile terminals are the mobile phones and other devices that support the LTE standard.
Radio Interface: Radio interface is a wireless connection between the LTE



mobile terminals and eNodeB. It is wireless signals that form the mobile cells.
eNodeB: E-UTRAN Node B or eNodeBs are situated all over the network of the mobile operator. They connect the LTE mobile terminal via radio interface to the core network.

Core Network for LTE

Core Network is the brain of the system. It is formed of telephony switches that enable the different services for the mobile users. Core network devices connect the mobile devices in the mobile network. They also connect the mobile network with the fixed telephony network and internet. The LTE core network is called EPC (Evolved Packet Core) or System Architecture Evolution (SAE). The core network is formed from the five nodes:

MME: Mobility Management Entity or MME is the central control node in the EPC network. It is responsible for mobility and security signalling, tracking and paging of mobile terminals.
S-GW: Serving Gateway or S-GW transports the user traffic between the mobile terminals and external networks. It also interconnects the radio access network with the EPC network. It is connected to the P-GW.
P-GW: PDN (Packet Data Network) Gateway connects the EPC network to the external networks. It routes traffic to and from PDN networks.
HSS: HSS (Home Subscriber Server) is the database of all mobile users that includes all subscriber data. It is also responsible for authentication and call and session setup.
PCRF: PCRF (Policy and Charging Rules Function) is node responsible for real-time policy rules and charging in EPC network.

3 Architecture of 4G-LTE

The LTE model has been designed to support the evaluation of the following aspects of LTE systems:

1. **Radio Resource Management**

2. **QoS-aware Packet Scheduling**

3. **Inter-cell Interference Coordination**

4. **Dynamic Spectrum Access**

In order to model LTE systems to a level of detail that is sufficient to allow a correct evaluation of the above mentioned aspects, the following requirements have been considered:

1. At the radio level, the granularity of the model should be at least that of the Resource Block (RB). In fact, this is the fundamental unit being used for resource allocation. Without this minimum level of granularity, it is not possible to model accurately packet scheduling and inter-cell-interference. The reason is that, since packet scheduling is done on a per-RB basis, an eNB might transmit on a subset only of all the available RBs, hence interfering with other eNBs only on those RBs where it is transmitting. Note that this requirement rules out the adoption of a system level simulation approach, which evaluates resource allocation only at the granularity of call/bearer establishment.

2. The simulator should scale up to tens of eNBs and hundreds of User Equipment (UEs). This rules out the use of a link level simulator, i.e., a simulator whose radio interface is modeled with a granularity up to the symbol level. This is because to have a symbol level model it is necessary to implement all the PHY layer signal processing, whose huge computational complexity severely limits simulation. In fact, link-level simulators are normally limited to a single eNB and one or a few UEs.

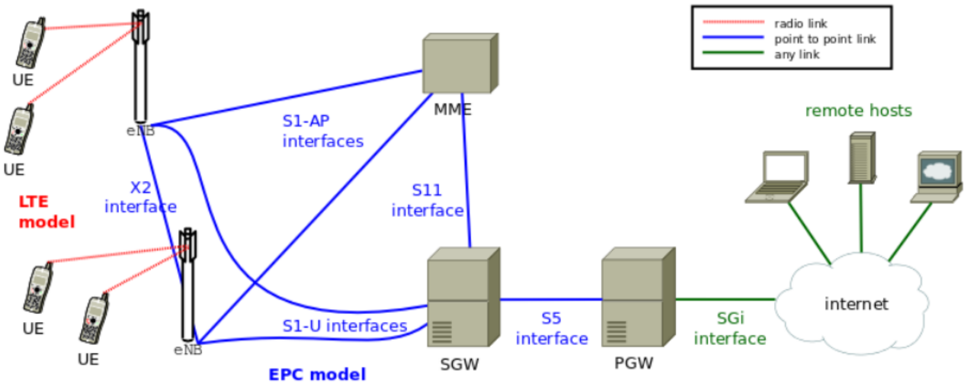
3. It should be possible within the simulation to configure different cells so that they use different carrier frequencies and system bandwidths. The bandwidth used by different cells should be allowed to overlap, in order to support dynamic spectrum licensing solutions. The calculation of interference should handle appropriately this case.

4. To be more representative of the LTE standard, as well as to be as close as possible to real-world implementations, the simulator should support the MAC Scheduler API published by the FemtoForum [FFAPI]. This interface is expected to be used by femtocell manufacturers for the implementation of scheduling and Radio Resource Management (RRM) algorithms. By introducing support for this interface in the simulator, we make it possible for LTE equipment vendors and operators to test in a simulative environment exactly the same algorithms that would be deployed in a real system.

5. The LTE simulation model should contain its own implementation of the API defined in [FFAPI]. Neither binary nor data structure compatibility with vendor-specific implementations of the same interface are expected; hence, a compatibility layer should be interposed whenever a vendor-specific MAC scheduler is to be used with the simulator. This requirement is necessary to allow the simulator to be independent from vendor-specific implementations of this interface specification.
6. The model is to be used to simulate the transmission of IP packets by the upper layers. With this respect, it shall be considered that in LTE the Scheduling and Radio Resource Management do not work with IP packets directly, but rather with RLC PDUs, which are obtained by segmentation and concatenation of IP packets done by the RLC entities. Hence, these functionalities of the RLC layer should be modeled accurately.

1. **High throughput :** High data rates can be achieved in both downlink as well as uplink. This causes high throughput.

2. **Low latency :** Time required to connect to the network is in range



Overview of the LTE-EPC simulation model

of a few hundred milliseconds and power saving states can now be entered and exited very quickly.

3. **FDD and TDD in the same platform :** Frequency Division Duplex (FDD) and Time Division Duplex (TDD), both schemes can be used on same platform.

4. **Superior end-user experience :** Optimized signaling for connection establishment and other air interface and mobility management procedures have further improved the user experience. Reduced latency (to 10 ms) for better user experience.

5. **Seamless Connection :** LTE will also support seamless connection to existing networks such as GSM, CDMA and WCDMA.

6. **Plug and play :** The user does not have to manually install drivers for the device. Instead system automatically recognizes the device, loads new drivers for the hardware if needed, and begins to work with the newly connected device.

Simple architecture : Because of Simple architecture low operating expenditure (OPEX).

3.1 EPC model

The main objective of the EPC model is to provides means for the simulation of end-to-end IP connectivity over the LTE model. To this aim, it supports for the interconnection of multiple UEs to the Internet, via a radio access network of multiple eNBs connected to the core network.

The following design choices have been made for the EPC model:

1. The Packet Data Network (PDN) type supported is both IPv4 and IPv6. In other words, the end-to-end connections between the UEs and the remote hosts can be IPv4 and IPv6. However, the networks between the core network elements (MME, SGWs and PGWs) are IPv4-only.

2. The SGW and PGW functional entities are implemented in different nodes, which are hence referred to as the SGW node and PGW node, respectively.

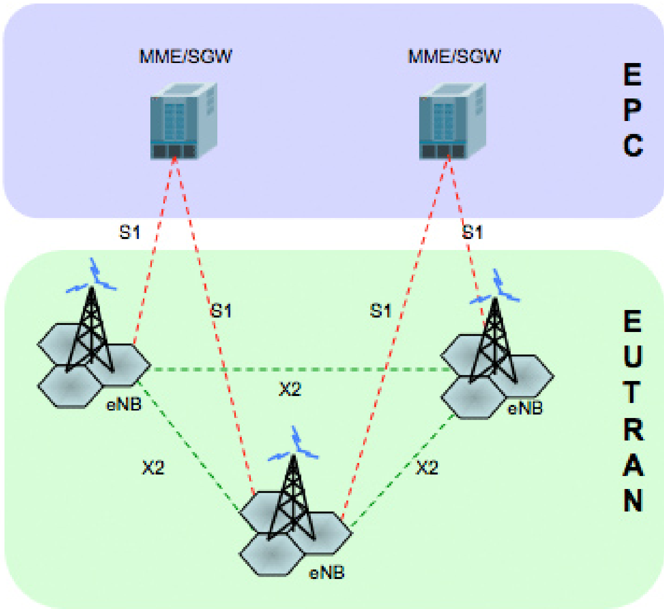
3. The MME functional entities is implemented as a network node, which is hence referred to as the MME node.

4. The scenarios with inter-SGW mobility are not of interest. But several SGW nodes may be present in simulations scenarios.

5. A requirement for the EPC model is that it can be used to simulate the end-to-end performance of realistic applications. Hence, it should be possible to use with the EPC model any regular ns-3 application working on top of TCP or UDP.

6. Another requirement is the possibility of simulating network topologies with the presence of multiple eNBs, some of which might be equipped with a backhaul connection with limited capabilities. In order to simulate such scenarios, the user data plane protocols being used between the eNBs and the SGW should be modeled accurately.

7. It should be possible for a single UE to use different applications with different QoS profiles. Hence, multiple EPS bearers should be supported for each UE. This includes the necessary classification of TCP/UDP traffic over IP done at the UE in the uplink and at the PGW in the downlink.



8. The initial focus of the EPC model is mainly on the EPC data plane. The accurate modeling of the EPC control plane is, for the time being, not a requirement; however, the necessary control plane interactions among the different network nodes of the core network are realized by implementing control protocols/messages among them. Direct interaction among the different simulation objects via the provided helper objects should be avoided as much as possible.

9. The focus of the EPC model is on simulations of active users in ECM connected mode. Hence, all the functionality that is only relevant for ECM idle mode (in particular, tracking area update and paging) are not modeled at all.

10. The model should allow the possibility to perform an X2-based handover between two eNBs.

3.2 THE E-UTRAN

The architecture of evolved UMTS Terrestrial Radio Access Network (E-UTRAN) has been illustrated below.

The E-UTRAN handles the radio communications between the mobile and the evolved packet core and just has one component, the evolved base stations, called **eNodeB** or **eNB**. Each eNB is a base station that controls the mobiles in one or more cells. The base station that is communicating with a mobile is known as its serving eNB.

LTE Mobile communicates with just one base station and one cell at a time and there are following two main functions supported by eNB:

* The eBN sends and receives radio transmissions to all the mobiles using the analogue and digital signal processing functions of the LTE air interface.

* The eNB controls the low-level operation of all its mobiles, by sending them signalling messages such as handover commands.

Each eBN connects with the EPC by means of the S1 interface and it can also be connected to nearby base stations by the X2 interface, which is mainly used for signalling and packet forwarding during handover.

A home eNB (HeNB) is a base station that has been purchased by a user to provide femtocell coverage within the home. A home eNB belongs to a closed subscriber group (CSG) and can only be accessed by mobiles with a USIM that also belongs to the closed subscriber group.

4 Resource allocation in 4G

Scheduling is a central part of an LTE system. For each time instant, the scheduler determines to which user(s) the shared timeefrequency resource should be assigned and determines the data rate to use for the transmission. The scheduler is a key element and to a large degree determines the overall behavior of the system. Both uplink and downlink transmissions are scheduled and, consequently, there is a downlink and an uplink scheduler in the eNodeB.

The **downlink scheduler** is responsible for dynamically controlling the device(s) to transmit to. Each of the scheduled devices is provided with a

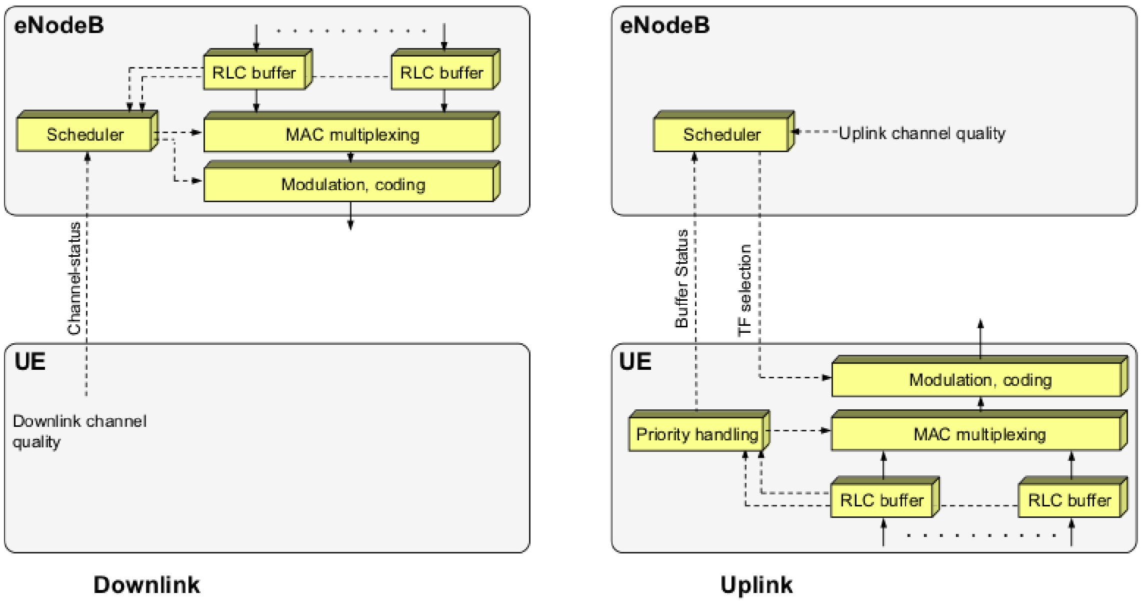


Figure 3: **Transport format selection in downlink and uplink**

scheduling assignment con- sisting of the set of resource blocks upon which the device's DL-SCH is transmitted, and the associated transport-format. The basic mode of operation is the so-called dynamic sched- uling, where the eNodeB for each 1 ms TTI conveys scheduling assignments to the selected devices using the (E)PDCCHs as described in Chapter 6, but there is also a possibility for semi-persistent scheduling to reduce the control-signaling overhead. Downlink scheduling assignments and logical channel multiplexing are controlled by the eNodeB.

The **uplink scheduler** serves a similar purpose, namely to dynamically control which devices are to transmit on their UL-SCH. Similarly to the downlink case, each scheduled device is provided with a scheduling grant consisting of the set of resource blocks upon which the device should transmit its UL-SCH and the associated transport-format. Also in this case, either dynamic or semi-persistent scheduling can be used. The uplink scheduler is in complete control of the transport format the device shall use but, unlike the downlink case, not the logical-channel multiplexing. Instead, the logical-channel multiplexing is controlled by the device according to a set of rules. Thus, uplink scheduling is per device and not per radio bearer.

4.1 Scheduling Strategies

The scheduling strategy in LTE is not standardized but is a base-station-implementation issuedand an important one as the scheduler is a key element in LTE and to a large extent defines the overall behavior. Different vendors may choose different strategies in various scenarios to match the user needs. What is standardized is the supporting functions for scheduling such as transmission of scheduling grants, quality-of-service mechanisms, and various feedback information, for example channel-state reports and buffer-status reports. However, there are some basic scheduling strategies in the literature, useful to illustrate the principles.

For the purpose of illustrating the principles, consider time-domain-only scheduling with a single user being scheduled at a time and all users having an infinite amount of data to transmit. In this case, the utilization of the radio resources is maximized if, at each time instant, all resources are assigned to the user with the best instantaneous channel condition. Together with rate control, this implies that the highest data rate is achieved for a given transmit power or, in other words, for a given interference to other cells, the highest link utilization is achieved. Rate control is more efficient compared to power control, which adjusts the transmission power to follow the channel variations while keeping the data rate constant. This scheduling strategy is an example of channel-dependent scheduling known as **max-C/I (or maximum rate) scheduling**.

Since the radio conditions for the different radio links within a cell typically vary independently, at each point in time there is almost always a radio link whose channel quality is near its peak and supporting a correspondingly high data rate. This translates into a high system capacity. The gain obtained by transmitting to users with favorable radio-link conditions is commonly known as multi-user diversity; the multi-user diversity gains are larger, the larger the channel variations and the larger the number of users in a cell. Hence, in contrast to the traditional view that rapid variations in the radio-link quality is an undesirable effect that has to be combated, the possibility of channel- dependent scheduling implies that rapid variations are in fact potentially beneficial and should be exploited.
Mathematically, the max-C/I scheduler can be expressed as scheduling user k given by

$$\mathbf{k = arg\ max\ R}$$

where R i is the instantaneous data rate for user i. Although, from a system capacity perspective, max- C/I scheduling is beneficial, this scheduling principle will not be fair in all situations. If all devices are, on average, experiencing similar channel conditions and the variations in the instantaneous channel conditions are only due to, for example, fast multi-path fading, all users will experience the same average data rate. Any variations in the instantaneous data rate are rapid and often not even noticeable by the user. However, in practice different devices will also experience differences in the (short-term) average channel conditionsdfor example, due to differences in the distance between the base station and the device. In this case, the channel conditions experienced by one device may, for a relatively long time, be worse than the channel conditions experienced by other devices. A pure max-C/I-scheduling strategy would then "starve" the device with the bad channel conditions, and the device with bad channel conditions will never be scheduled. where a max-C/I scheduler is used to schedule between two different users with different average channel quality. Although resulting in the highest system capacity, this situation is often not acceptable from a quality-of-service point of view.

An alternative to the max-C/I scheduling strategy is so-called **round-robin scheduling**. This scheduling strategy lets users take turns in using the shared resources, without taking the instantaneous channel conditions into account. Round-robin scheduling can be seen as fair scheduling in the sense that the same amount of radio re- sources (the same amount of time) is given to each communication link. However, round- robin scheduling is not fair in the sense of providing the same service quality to all communication links. In that case more radio resources (more time) must be given to communication links with bad channel conditions. Furthermore, as round-robin scheduling does not take the instantaneous channel conditions into account in the scheduling process, it will lead to lower overall system performance but more equal service quality between different communication links, compared to max-C/I scheduling.

A third possibility is the so-called proportional fair scheduler, see Figure 9.2(c), which tries to exploit rapid channel variations while suppressing the effect of differences in the average channel gain. In this strategy, the shared resources are assigned to the user with the relatively best radio-link conditionsdthat is, at each time instant, user k is selected for transmission according to

$$\mathbf{k = arg\ max(Ri/Ra)}$$

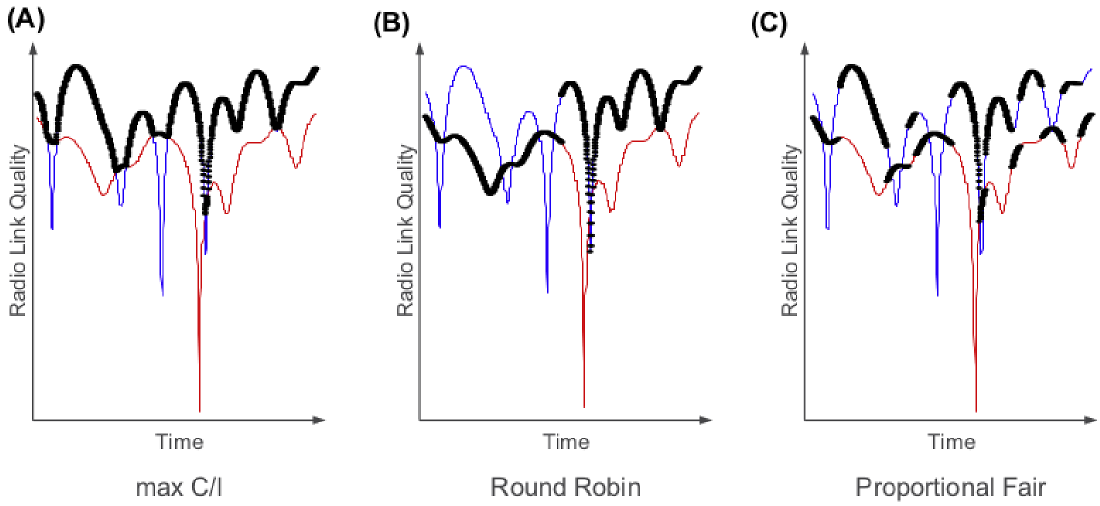


Figure 4: **Example of three different scheduling behaviors for two users with different average channel quality**

where R i is the instantaneous data rate for user i and R i is the average data rate for user i. The average is calculated over a certain averaging period long enough to average out differences in the fast channel- quality variations and at the same time short enough so that quality variations within the interval are not strongly noticed by a user.

the degree of fairness introduced by the traffic properties depends heavily on the actual traffic; a design made with certain assumptions may be less desirable in an actual network where the traffic pattern may be different from the assumptions made during the design. Therefore, relying solely on the traffic properties to achieve fairness is not a good strategy, but the discussion above also emphasizes the need to design the scheduler not only for the full buffer case. Traffic priorities, for example prioritizing a latency-critical services over a delay-tolerant service despite the channel quality for the latter being superior, is another example where the full-buffer discussion above was simplified to illustrate the basic principles. Other examples of scheduling input are DRX cycles, retransmissions, device capabilities, and device power consumption, all impacting the overall scheduling behavior.

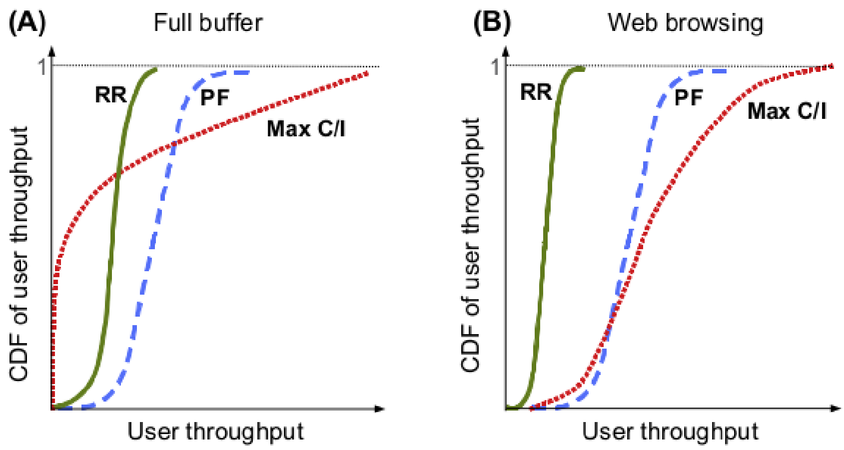


Figure 5: **principle behavior of different scheduling strategies**

4.2 Downlink scheduling

The task of the downlink scheduler is to dynamically determine the device(s) to transmit to and, for each of these devices, the set of resource blocks upon which the device's DL-SCH should be transmitted. As discussed in the previous section, the amount of data in the transmission buffers as well as the desire to exploit channel-variations in the frequency domain implies that transmissions to multiple users in different parts of the spectrum is needed. Therefore, multiple devices can be scheduled in parallel in a subframe, in which case there is one DL-SCH per scheduled device (and component carrier), each dynamically mapped to a (unique) set of frequency resources.

The scheduler is in control of the instantaneous data rate used, and the RLC segmentation and MAC multiplexing will therefore be affected by the scheduling decision. Although formally part of the MAC layer but to some extent better viewed as a separate entity, the scheduler is thus controlling most of the functions in the eNodeB associated with downlink data transmission:

- **RLC :** Segmentation/concatenation of RLC SDUs is directly related to the instantaneous data rate. For low data rates, it may only be possible to deliver a part of an RLC SDU in a TTI, in which case segmentation is needed. Similarly, for high data rates, multiple RLC

SDUs may need to be concatenated to form a sufficiently large transport block.

- **MAC :** Multiplexing of logical channels depends on the priorities between different streams. For example, radio resource control signaling, such as handover commands,typically has a higher priority than streaming data, which in turn has higher priority than a background file transfer. Thus, depending on the data rate and the amount of traffic of different priorities, the multiplexing of different logical channels is affected. Hybrid-ARQ retransmissions also need to be accounted for.

- **L1 :** Coding, modulation, and, if applicable, the number of transmission layers and the associated precoding matrix are affected by the scheduling decision. The choices of these parameters are mainly determined by the radio conditions and the selected data rate, that is, the transport block size.

The scheduling strategy is implementation-specific . However, the overall goal of most schedulers is to take advantage of the channel variations between devices and preferably to schedule transmissions to a device when the channel conditions are ad- vantageous. Most scheduling strategies therefore at least need information about:

● channel conditions at the device;
● buffer status and priorities of the different data flows;
● the interference situation in neighboring cells (if some form of interference coordination is implemented).

Information about the channel conditions at the device can be obtained in several ways. In principle, the eNodeB can use any information available, but typically the CSI reports from the device are used. Other sources of channel knowledge, for example, exploiting channel reciprocity to estimate the downlink quality from uplink channel estimates in the case of TDD, can also be exploited by a particular scheduler implementation, either alone or in combination with CSI reports.

In addition to the channel-state information, the scheduler should take buffer status and priority levels into account. For example, it does not make sense to schedule a device with empty transmission buffers. Priorities of the different types of traffic may also vary; RRC signaling may be prioritized over user data. Furthermore, RLC and hybrid-ARQ retrans- missions, which are in no way different from other types of data from a scheduler perspective, are typically also given priority over initial transmissions.

Downlink inter-cell interference coordination is also part of the implementation-specific scheduler strategy. A cell may signal to its neighboring cells the intention to transmit with a lower transmission power in the downlink on a set of resource blocks. This information can then be exploited by neighboring cells as a region of low interference where it is ad- vantageous to schedule devices at the cell edge, devices that otherwise could not attain high data rates due to the interference level.

4.3 Uplink scheduling

The basic function of the uplink scheduler is similar to its downlink counterpart, namely to dynamically determine, for each 1 ms interval, which devices are to transmit and on which uplink resources. As discussed before, the LTE uplink is primarily based on maintaining orthogonality between different uplink transmissions and the shared resource controlled by the eNodeB scheduler is timeefrequency resource units. In addition to assigning the timeefrequency resources to the device, the eNodeB scheduler is also responsible for con- trolling the transport format the device will use for each of the uplink component carriers. This allows the scheduler to tightly control the uplink activity to maximize the resource usage compared to schemes where the device autonomously selects the data rate, as autonomous schemes typically require some margin in the scheduling decisions. A consequence of the scheduler being responsible for selection of the transport format is that accurate and detailed knowledge in the eNodeB about the device situation with respect to buffer status and power availability is more accentuated in LTE compared to systems where the device autonomously controls the transmission parameters.

The basis for uplink scheduling is scheduling grants, containing the scheduling decision and providing the device information about the resources and the associated transport format to use for transmission of the UL-SCH on one component carrier. Only if the device has a valid grant is it allowed to transmit on the corresponding UL-SCH; autonomous transmissions are not possible. Dynamic grants are valid for one subframe, that is, for each subframe in which the device is to transmit on the UL-SCH, the scheduler issues a new grant.

Similarly to the downlink case, the uplink scheduler can exploit information about channel conditions, and, if some form of interference coordination is employed, the interference situation in neighboring cells. Information about the buffer status in the device, and its available transmission power, is also beneficial to the scheduler. This calls for the reporting mechanisms described in the following, unlike the downlink case where the scheduler, power amplifier, and transmission buffers all are in the same node. Uplink priority handling is, as already touched upon, another area where uplink and downlink scheduling differs.

Channel-dependent scheduling, which typically is used for the downlink, can be used for the uplink as well. In the uplink, estimates of the channel quality can be obtained from the use of uplink channel sounding. For scenarios where the overhead from channel sounding is too costly, or when the variations in the channel are too rapid to be tracked, for example at high device speeds, uplink diversity can be used instead.

Throughput is the rate of production or the rate at which something is processed.

When used in the context of communication networks, such as Ethernet or packet radio, throughput or network throughput is the rate of successful message delivery over a communication channel. The data these messages belong to may be delivered over a physical or logical link, or it can pass through a certain network node. Throughput is usually measured in bits per second (bit/s or bps), and sometimes in data packets per second (p/s or pps) or data packets per time slot.

5 Parameters in 4G

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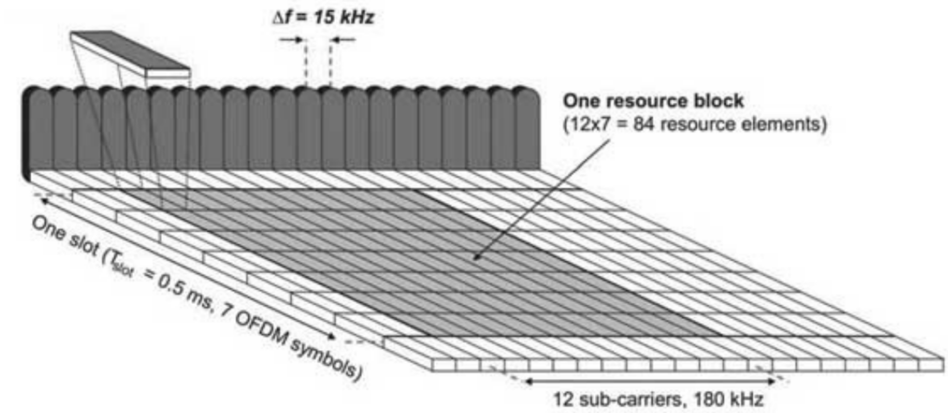

Figure 6: **Resource block in frequency and time domain**

5.1 Characteristics of OFDMA/SC-FDMA system:

1. LTE Radio Frame duration = 10ms
2. Sub-frame duration = 1ms
3. Time Slot duration = 0.5ms
4. Symbol duration = 0.5ms / 7
5. Symbol count = 7 in normal CP
6. Subcarrier bandwidth = 15 KHz
7. Subcarrier count in one PRB = 12
8. Transmission Time Interval = 1ms (minimum scheduling time for user, 2 PRB at once)

5.2 Downlink Throughput :

System availability :

- Modulation = 64QAM (6 bits can be carried on each RE with this modulation)
- Antenna = 2T2R MIMO

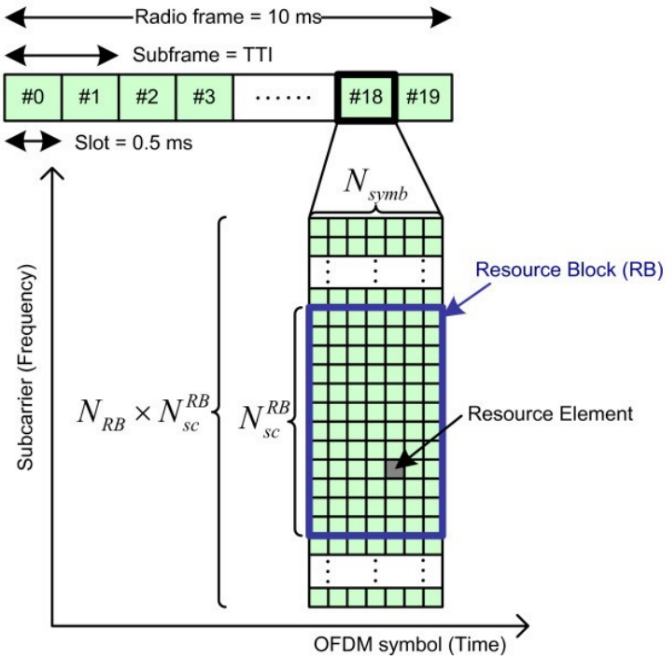

Figure 7: **LTE Frame format in Time and Frequency Domains**

- Bandwidth = 20MHz (100 PRB and 1200 subcarriers are exist in 20MHz)

Calculation :

- Number of bits in one PRB = subcarriers * symbols * bits = 12 * 7 * 6 = 504 bits (0.5ms)
- Minimum scheduling for user = 504 bits (0.5ms) + 504 bits (0.5ms) = 1008 bits per ms
- Number of bits in whole bandwidth = #PRB * bits = 100 * 1008 = 100800 bits per ms
- Transmission is 2T2R MIMO = 2 * 100800 = 201600 bits per ms by two transmission
- Other channels, occupy 25% of whole resource = 151200 bits per ms = **151.2 mbps**

5.3 Uplink Throughput :

System availability :

- Modulation = 16QAM (4 bits per RE, most of the commercial UE support max 16QAM)
- Antenna = 1T1R SISO
- Bandwidth = 20MHz (100 PRB and 1200 subcarriers are exist in 20MHz)

Calculation :

- Number of bits in one PRB = subcarriers * symbols * bits = 12 * 7 * 4 = 336 bits (0.5ms)
- Minimum scheduling for user = 336 bits (0.5ms) + 336 bits (0.5ms) = 672 bits per ms
- Number of bits in whole bandwidth = #PRB * bits = 100 * 672 = 67200 bits per ms
- Other channels, occupy 25% of whole resource = 50400 bits per ms =**50.4 Mbps**

6 Real time issues in 4G

In the 4G - Networks , different types of wireless networks are interconnected to support handoff from one technology to another. These wireless systems were designed independently and targeting different service types, data rates, and users, and thus require an intelligent interworking approach. Effective, secure and efficient operations and management are the major challenge for the development of 4G.

In such environment, both the mobile user and the interconnected wireless networks together play an important role in determining how service continuity and service quality can be served in a handover and helps in providing best service to the user. There are number of research challenges which need to be solved in order to achieve 4G network goals. These challenges are listed below :

1. **Network Discovery :** 4G Network devices will be multi- mode, multi-access and reconfigurable. Which means each termi- nal can be using more than one type of network and possibly can access multiple networks simultaneously for different applications. In such an environment, a terminal must be able to discover what networks are available for use. As a solution to this issue currently a technique namely Software defined radio is proposed. In this technique components that have been implemented in hardware are instead implemented using software on a personal computer or other embedded computing devices.

2. **Access technologies :** 4G- network is a heterogeneous wire- less environment consist of number of radio technologies and may have overlapped radio coverage. A mobile user needs to switch be- tween access networks to maintain service continuity and optimise service quality. Dealing with heterogeneous access technologies is a challenge to the design of 4G Network. More over selecting the network that will satisfy the QoS requirements of the current service and that will be the most economical.

3. **Network architectures :** 4G is an integration of hetero- geneous wireless networks. Moreover these networks rely on dif- ferent network architectures and protocols for transport, routing, mobility management and so forth. The interconnection of these 12networks in an integral manner to facilitate the cooperation be- tween them is another research challenge.

4. **Network conditions :** Network conditions such as band- width, delay, jitter and so forth may vary across wireless networks, and result in different service quality to be provided. How does a mobile user deal with the variation in network conditions, and maintain service quality when crossing heterogeneous wireless net- works is needs to be addressed.

5. **Charging and Billing :** In the 4G network environment multiple service providers will be involved during a session, if the users roam

from one service provider network to one or more other service provider networks. Thus, a single session may consist of number of charges. Moreover, different charging schemes maybe used for different types of services. One challenge is to keep track of charges per use per segment of a session that used their net- work, service or content. There will need to be more charging agreements between the service providers in order to allow roam- ing during a session in order to get a continued service as far as a customer is concerned.

6. **Large number of operators :** A large number of network operators are expected to co-exist and collaborate in the 4G - Net- works. In such circumstances, mobile users who are responsible for handover decision will require increased levels of control over how services can be secured in handover. This will be complicated by versatile trust relationships between network operators.

7. **Congestion Control :** Congestion control is another crit- ical issue in 4G - networks. Avoidance or prevention of the con- gestion and detection and recovery after congestion are two basic approaches taken towards the congestion control. The avoidance scheme will require the network to suitably implement the admis- sion control and scheduling techniques. The detection and recov- ery would require flow control and feedback traffic management.

8. **Quality of service :** Quality of service is more important for 4G networks as we know that telecommunication is a real time communication like Voice over IP and video streaming .In real time traffics quality of service is very important as we should estimate some factors like bit rate, jitter, delay, packet drop probability to avoid network congestion in available bandwidth effectively.

9. **Handover:**Handovers is defined as the switching of mobile nodes (MN) from one access point to other in current network or to a different network.4G networks faces lot of challenges while handover in today's communication systems. In particular if a mobile user is undergone handover process from communication systems like GPRS to WLAN at that time there is a potential risk of communication disturbance which makes the mobile user unhappy.

10. **Potential solutions :** As we know that 4G networks are heterogeneous networks they support different functions to network operators and service providers. So to provide security for communication 4G

networks introduce security gateways (SEGs) which secure the different domains. For developing security in 4G networks we should adopt a model developed by International Telecommunication union named as X.805 based on Bell lab security model which consist of three security layers, three security planes and eight security dimensions which has explained below.

7 Network Simulator

A network simulator is software that predicts the behavior of a computer network. Since communication networks have become too complex for traditional analytical methods to provide an accurate understanding of system behavior, network simulators are used. In simulators, the computer network is modeled with devices,links, applications etc. and the network performance is reported. Simulators come with support for the most popular technologies and networks in use today such as 4G, Internet of Things (IoT), Wireless LANs, mobile ad hoc networks, wireless sensor networks, vehicular ad hoc networks, cognitive radio networks, LTE etc.

A simulation for 4G-LTE architecture is done on **NETWORK SIMULATOR-3** as shown in the figure given above :- In this simulation we define the following nodes :

- **INTERNET NODE**
- **8 UE-NODEs**
- **3 ENB-NODEs**
- **S-GW NODE**
- **P-GW NODE**
- **MME NODE**

The P-GW ,S-GW and MME node are the nodes in **EPC (EVOLVED PACKET CORE)** and the UE-NODES and ENB-NODES are the nodes in E-UTRAN .

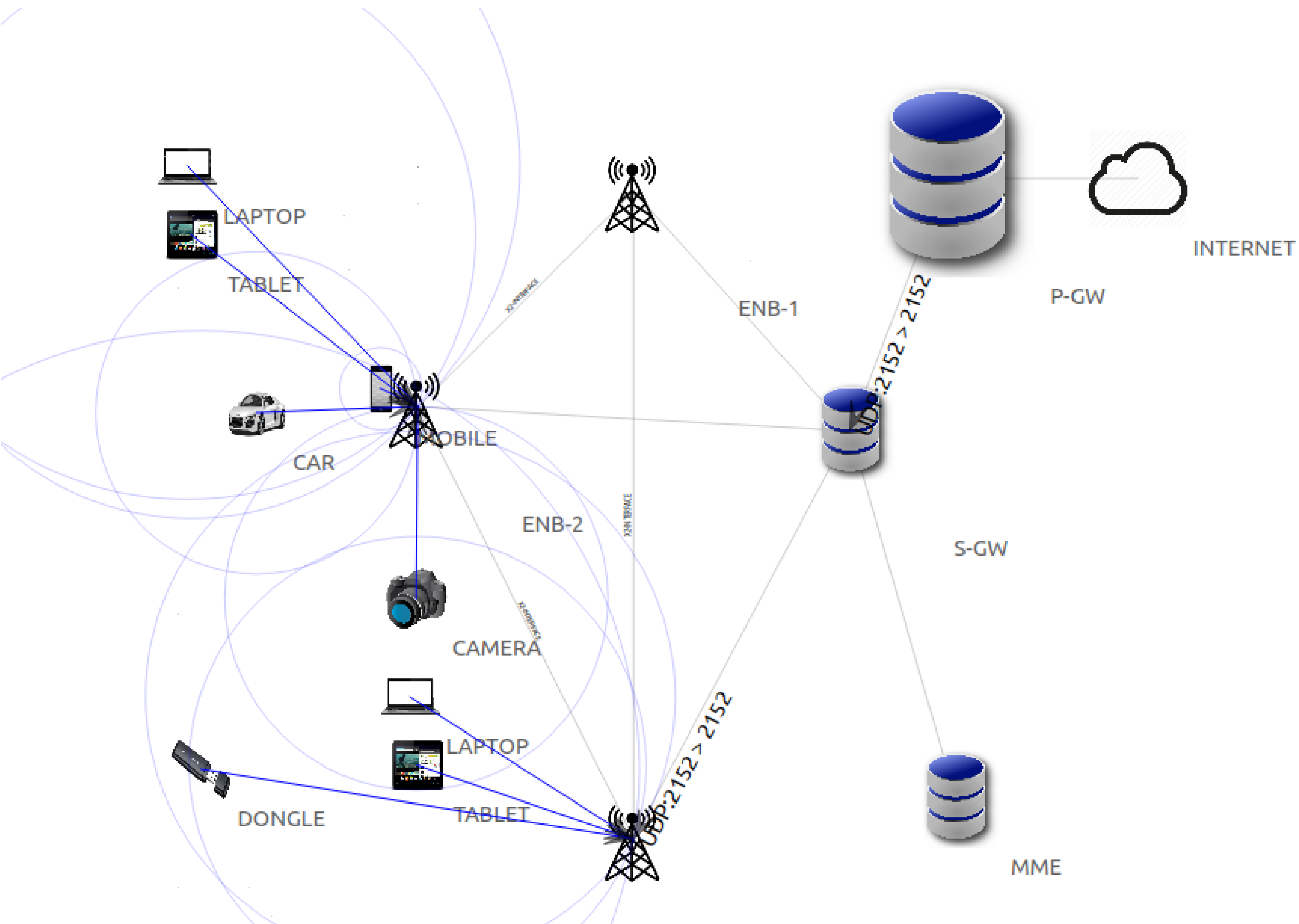

Figure 8: **Simulation on Network Simulator-3**

A C++ high level language is used for coding for this simulation . The code for this Simulation is of 444 lines which contains many functions from defining the NODES to attach them and to install APPLICATIONs and providing IP addresses to them.

In this simulation we use the **ADAPTIVE TOKEN BUCKET (TBFQ)** Scheduler for the distribution of resource blocks to the UE-NODES.

TBFQ is a channel aware/Qos aware scheduler which is derived from leaky bucket machanisms.
In this QOS is gauranteed by setting token generation rate to different values.
In TBFQ, flows belonging to UEs that are suffering from severe interference , and shadowing conditions in particular, will have a highest priority metric

It uses the **A2A4Rsrq Handover Algorithm** for the handover procedure between the ENB-NODES of UE-NODES.

The links between S-GW and E-NBs are the **Point To Point Links** having Data rate 10Gb/ps.

Each UE in this simulation have different QoS parameters and have their own dedicated bearers. so they have different RxBytes and TxBytes based on their QoS parameters.

7.1 LTE traces

As we can see in the Simulation the different graphics which are showing the movement of packets from one node to another .

Also in the NS-3 simulation of Lte we can trace the PHY, MAC, RLC and PDCP level Key Performance Indicators (KPIs) .

RLC and PDCP KPIs are calculated over a time interval and stored on ASCII files, two for RLC KPIs and two for PDCP KPIs, in each case one for uplink and one for downlink.

The columns of the RLC KPI files is the following (the same for uplink and downlink):

- start time of measurement interval in seconds since the start of simulation
- end time of measurement interval in seconds since the start of simulation
- Cell ID
- unique UE ID (IMSI)
- cell-specific UE ID (RNTI)
- Logical Channel ID
- Number of transmitted RLC PDUs
- Total bytes transmitted.
- Number of received RLC PDUs
- Total bytes received
- Average RLC PDU delay in seconds
- Standard deviation of the RLC PDU delay
- Minimum value of the RLC PDU delay
- Maximum value of the RLC PDU delay
- Average RLC PDU size, in bytes
- Standard deviation of the RLC PDU size
- Minimum RLC PDU size
- Maximum RLC PDU size

Similarly, the columns of the PDCP KPI files is the following (again, the same for uplink and downlink):

- start time of measurement interval in seconds since the start of simulation

- end time of measurement interval in seconds since the start of simulation
- Cell ID
- unique UE ID (IMSI)
- cell-specific UE ID (RNTI)
- Logical Channel ID
- Number of transmitted PDCP PDUs
- Total bytes transmitted.
- Number of received PDCP PDUs
- Total bytes received
- Average PDCP PDU delay in seconds
- Standard deviation of the PDCP PDU delay
- Minimum value of the PDCP PDU delay
- Maximum value of the PDCP PDU delay
- Average PDCP PDU size, in bytes
- Standard deviation of the PDCP PDU size
- Minimum PDCP PDU size
- Maximum PDCP PDU size

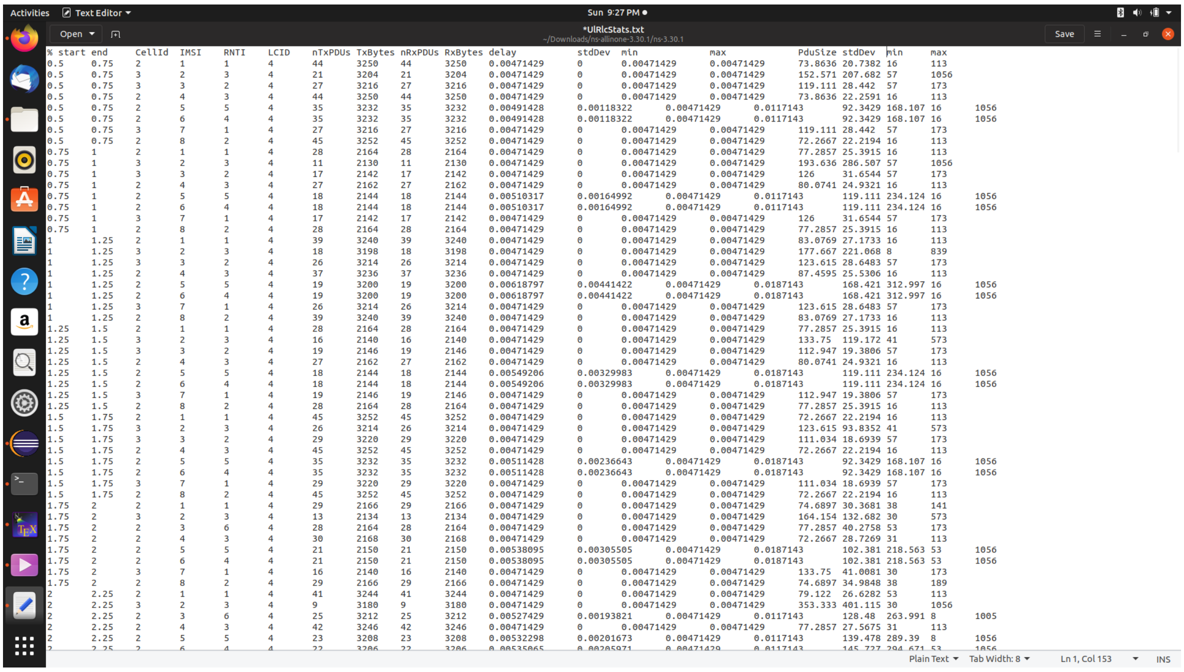

Figure 9: **Traces for Uplink RLC stats**

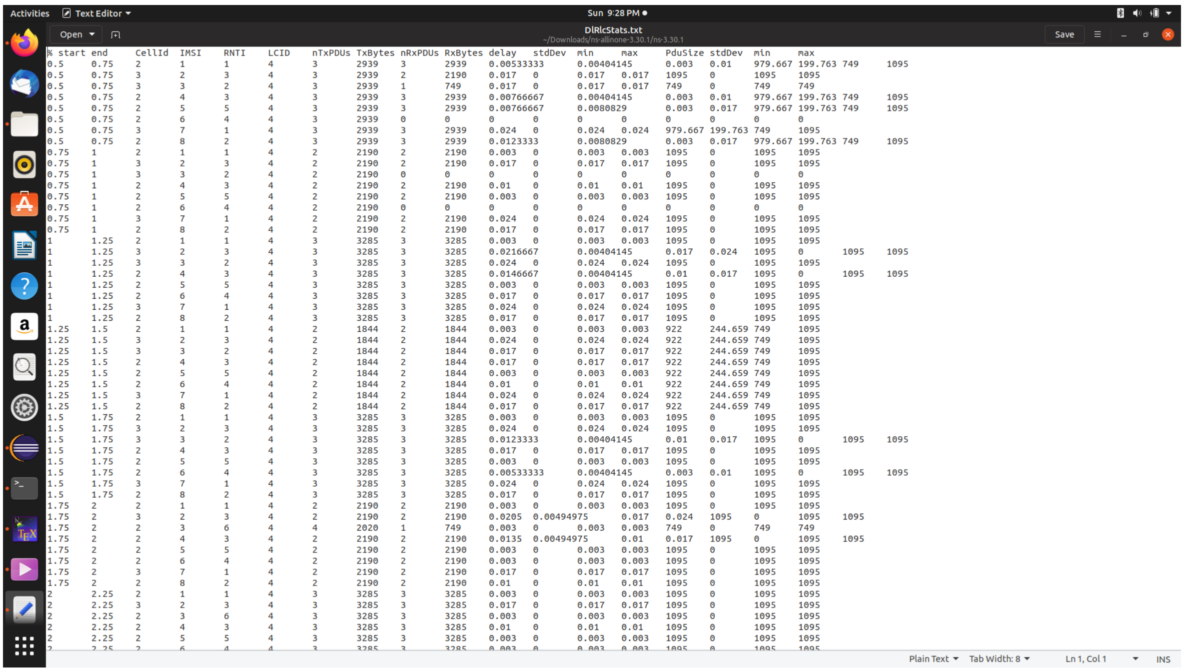

Figure 10: **Traces for DownLink RLC**

7.2 Flow monitor traces

The Flow Monitor goal is to provide a flexible system to measure the performance of network protocols. The module uses probes, installed in network nodes, to track the packets exchanged by the nodes, and it will measure a number of parameters. Packets are divided according to the flow they belong to, where each flow is defined according to the probe's characteristics (e.g., for IP, a flow is defined as the packets with the same protocol, source (IP, port), destination (IP, port) tuple.

The data collected for each flow are:

- **timeFirstTxPacket:** when the first packet in the flow was transmitted;
- **timeLastTxPacket:** when the last packet in the flow was transmitted;
- **timeFirstRxPacket:** when the first packet in the flow was received by an end node;
- **timeLastRxPacket:** when the last packet in the flow was received;
- **delaySum:** the sum of all end-to-end delays for all received packets of the flow;
- **jitterSum:** the sum of all end-to-end delay jitter (delay variation) values for all received packets of the flow, as defined in RFC 3393;
- **txBytes, txPackets:** total number of transmitted bytes / packets for the flow;
- **rxBytes, rxPackets:** total number of received bytes / packets for the flow;
- **lostPackets:** total number of packets that are assumed to be lost (not reported over 10 seconds);
- **timesForwarded:** the number of times a packet has been reportedly forwarded;
- **delayHistogram, jitterHistogram, packetSizeHistogram:** histogram versions for the delay, jitter, and packet sizes, respectively;

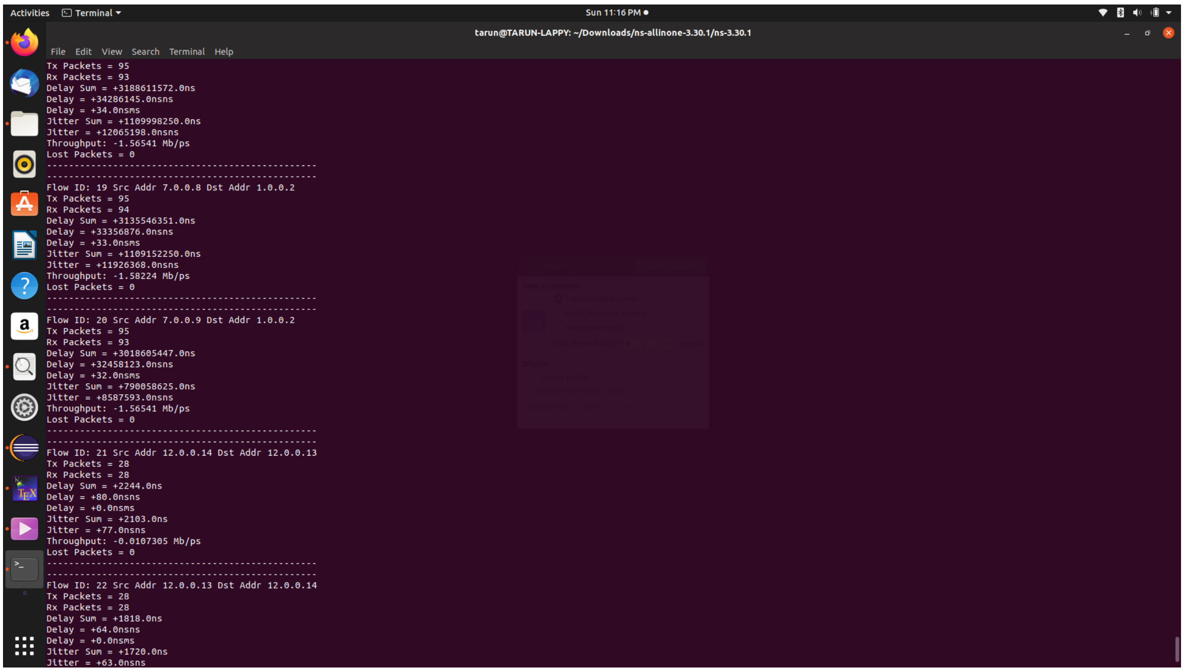

Figure 11: **Flow Monitor**

- **packetsDropped, bytesDropped:** the number of lost packets and bytes, divided according to the loss reason code (defined in the probe).

* Throughput calculation using flow monitor data.

Throughput = (rxBytes * 8.0*28) / (timeLastRxPacket-timeFirstTxPacket)*1000000

where :-

- 28 = Payload.
- rxBytes = Received Bytes.
- timeLastRxPacket = time when last packet is received.
- timeFirsTxPacket = time when First packet is transmitted.

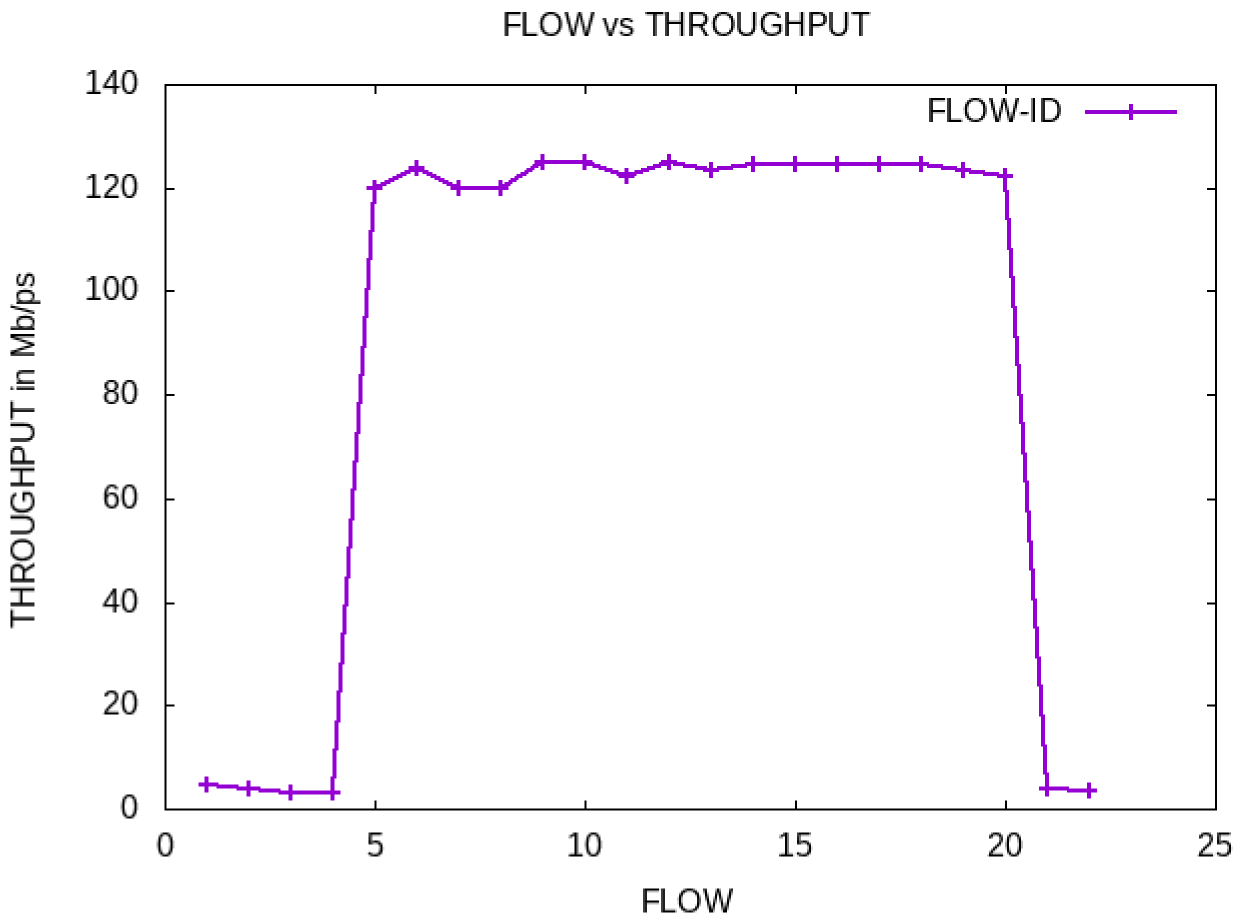

Figure 12: **Flow vs Throughput**

8 ECE-Labs Survey

8.1 Codes and signal design lab

In the codes and signal design lab, the current areas of research include error-correcting codes with a current emphasis on codes for distributed storage, wireless sensor networks and distributed function computation.The research is broadly based on principles of coding theory, information theory and wireless networks.

Codes for Distributed Storage: the distributed storage group has been and continues to be actively involved in studying problems faced in distributed storage systems.Our research is in part carried out in collaboration with NetApp.

Wireless Sensor Networks: The sensor network group's current primary focus is on designing and developing passive infra-red (PIR)-based WSNs for intrusion detection. Areas of research include lens design, intrusion simulation, machine-learning-based classification algorithms for intrusion detection. The work is sponsored in part by DeitY and in part by DRDO. The students in codes and signal design lab are guided by Prof. P. Vijay Kumar.

8.2 Network Labs

Faculty and students in network labs conduct research in the area of networks. While the primary emphasis over the past 25 years has been on analytical, algorithmic and experimental research in communication networking, in the recent years there have also be contributions to social networks, and road networks. These labs are organised as Network Engineering Lab (NEL) group conduct research on modelling, analysis, optimisation, and control problems arising in networks, with the aim being primarily theoretical and algorithmic contributions.
some researchs and project done by lab :

- **Hybrid MAC Protocols for Low-Delay Scheduling.**
  We consider the Medium Access Control (MAC) problem in resource - constrained ad-hoc wireless networks typical of the Internet Of Things (IoT). Due to delay-sensitive nature of emerging IoT aplications ,there

has been increasing interest in developing medium access control (TDMA) protocols in a slotted framework . The design of such MAC protocols must keep in mind the need for contention access at light traffic , and scheduled access in heavy traffic (leading to the long-standing interest in hybrid,adaptive MAC's).
Here we consider the collocated node setting and require that each node acts autonoumously only on the basis basis of locally available information .we propose EZMAC simpluy a extension of ZMAC and QZMAC which is designed using motivations from from our extensions of certain delay-optimality and throughput-optimality theory from the literature. Practical implementations issues are outlined. Finally,we show, through simulations , that both protocols acheive mean delays much lower than those acheived by ZMAC and indeed ,QZMAC provides mean delays very close to the minimum achiveable in this setting , i.e, that of the centralized complete knowledge scheduler.

- **Reduced-state,Optimal Medium Access Control for wireless Sensor Networks**

Motivated by medium access control for resource challenged wireless sensor networks whose main purpose is data collection , we consider the problem of queue scheduling with reduced queue state information .In particular , we consider a model with N sensor node , with a pair-wise dependence , such that nodes i and i+1 ,cannot transmit together for N= 3,4 and 5 , we develop new throughput optimal scheduling policies requiring only the empty-nonempty state of each queue , and also revisit previously proposed policies to rigoursly establish their throughput and delay -optimality. For N=3,there exist a sum queue. we show,however ,that for N>4 , there is no scheduling policy that uses only the empty-nonempty staes of the queues and is sum-queue length optimal uniformly over all arrival rate vectors . we then extend our results to a more general class of interference constraints , namely , a star of cliques. our Throughput -optimality reults rely on two new arguments : a lyapunov drift lemma specially adapted to policies that are queue length-agnostic , and a priority queueing analysis for showing strong stability .
we throughup some counter intuitive conclusions :
1. knowledge of queue length information is not necessary to acheive optimal throughput/delay performance for a large class of interference

networks,
2. It is possible to perform throughput optimal scheduling by merely knowing whether queues in the network are empty or not , and
3. It is also possible to be throughput-optimal by not always scheduling the maximum possible number of nonempty queues.

- **Coverage in One-Dimensional Wireless Networks with Infrastructure Nodes and Relay Extensions**

We consider a wireless network compromising two nodes namely as **sinks** and **relays** . The sinks are connected to the wireline infrastructure , while the relay nodes are used to extend the region covered by providing multi-hop paths to the sink nodes . Restricting to the one-dimensional setting,our objective is to chracacterize the fraction of covered region as a function of sink and relay nodes densities . We first compare and contrast our infrastructure - based model with the traditional setting where every node is a sink , and hence a location is covered if it simply lies within the range of some node Then, drawing an analogy between the connected components of the network and the busy periods of an M/D/infinity queue (and using renewal theoretic arguments) we derive a closed-form experssion for the average vacancy (complement of coverage).We also compute an upper bound for vacany by introducing the notion left-coverage a lower bound is derived by coupling our model with an independent-disk mode, where the sinks coverage regions are independent and identically distributed . Through an extensive theoreticl and numerical study,we study the problem of minimizing network deployment cost subject to a constraint on the average vacancy . We also conduct simulations to understand the properties of a general motion of coverage , obtained by introducing hop-counts into the definition Parametrized approximations for the hop-Constrained cluster lengths are proposed , whose efficency is evaluated numerically. In particular ,there exists a range of parameter values where our cluster-length approximation is good.Finally, hop-Constrained cost optimization is conducted too demonstrate the efficancy of the infrastructure -based design .

- **Performance of TCP Congestion Control with Ex-**

plicit Rate Feedback :

we consider a modification of TCP congestion control in which congestion window is adapted to explicit bottleneck rate feedback ; we call the RATCP(rate adaptive TCP). Our goal in this paper is to study and compare the performance of RATCP and TCP in various network scenarios with a view to understanding the possiblities and limits of providing better feedback to TCP than just implicit feedback via packet loss . To understand the dynamics of rate feedback and window control, we develop and a analyse a model for a long-lived RATCP(and TCP) session that gets a time-varying rate on a bottleneck link. We also conduct experiments on a linux based test-bed to study issues such as fairness,random losses , and randomly arriving short file transfers . We find that the analysis matches well with the results from the test-bed.For large file transfers, under low background load. ideal fair rate feedback improves the performance of TCP by 15%-20% . For small randomly arriving file transfers ,though RATCP performs only slightly better than TCP it reduces losses and variability

- **Combined Base Station Association and Power Control in Multichannel Cellular Networks**

  A combined base station association and power control problem is studied for the uplink of multichannel multicell cellular networks , in which each channel is used by exactly one cell. A distributed association and power update algorithm is proposed and shown to converge to a Nash equilibrium of a noncooperative gaem . We consider network models with discrete mobiles (yielding an atomic congestion game), as well as a continuum of mobiles (yielding a population game).We find that the equilibria need not be Pareto efficient , nor need they be system optimal. to address the lack of system optimality,we provide pricing mechanisms. It is shown that these mechanisms can elemented in a distributed fashion .

- ### Sequential Decision Algorithms for Measurement-Based Impromptu Deployment of a Wireless Relay Network Along a Line we are motivated by the need,in some applications ,for impromptu or as-you-go deployment of wireless sensor networks.A person walks along a line , starting from a sink node (e.g a base station), and proceeds towards a source node(e.g sensor) which is at an a priori unkown location. At equally spaced locations , he makes link quality measurements to the previous relay , and deploys relays at some of these locations, with the aim to connect the source to the sink by a multihop wireless path.

- **Adaptive optimal load balancing in a non-homogeneous multiserver system with a central job scheduler**

we consider a model comprising several servers, with possibly different service speeds , each equipped with its own queue. Each server receives a dedicated arrival stream of jobs; there is also a stream of generic jobs that arrive to a job scheduler and can be individually allocated to any of the servers. We show thst if the arrival streams are all poision , and all jobs have the same exponentially distributed service requirements . then the probalistic splitting of the generic stream that minimizes the average job response time is such that it balances the server idle times in a weighted least square sense, where the weighting coefficiets are related to the service speeds of the server. The corresponding result holds for nonexpo nentially distributed service times, if the service speeds are all equal.

- **Optimal Cross-Layer Scheduling Of Transmissions Over a Fading Multiaccess Channel**

We consider the problem of several users transmitting packets to a base station , and study and optimal scheduling formulation involving three communications layers, namely,the medium access control, link, and physical layers. We assume Markov models for the packet arrival processes and the channel gain processes. perfect channel state information is assumed too be available at the transmitter powe constraint.The control problem is to assign power and rate dynamically as a function of the fading and the queue lengths so as to minimize a weighted sum of long run average packet transmission delays.

Network Architecture Lab (NetArchLab) and **Network Applications Lab(NetAppsLab)** groups emphasizes on experimental work, system building, and test-beds. The algorithmic and analytical contributions required for the work in these labs comes from the work done in NEL. Some of the recent contributions include WLAN Manager, and its evolution, ADWISER (systems for managing enterprise wireless networks), and SmartConnect and 6PANview (systems for designing and managing sensor networks that arise in the Internet of Things).

Network Operations Lab (NetOpsLab) began in 1987 as a "point-of-presence" for India's first wide area packet network, namely ERNET. The NetOpsLab undertakes QoS monitoring and SLA management for the ERNET network.

The students and staff in network labs are guided by Prof. Anurag Kumar, Prof. Utpal Mukherji, and Dr. Malati Hegde.

8.3 Performance analysis lab

This lab focuses on modelling, analysis and design of communication systems. The current emphasis is on wireless communications. Phy, MAC and Network layer are considered in an integrated way to provide Quality of Service efficiently. The tools used are:Probability Theory,Statistics, Queueing Theory and Optimization. The problems encompass Communication Theory, Information Theory, Signal Processing and Communication Networks.

Research activities in this lab are guided by Prof. Vinod Sharma.

8.4 Coding and Modulation Lab

New coding and modulation techniques for wireless channels are proposed and their performance evaluated by analysis and simulation. New classes of network codes and network-error correcting codes are investigated.

Some research and project done by lab :

- ### Index Coded PSK Modulation for priortized Receviers

  A noisy coding problem (ICP) over additive white gaussians noise (AGWN) and Rayleigh fading channels is studied. First,a single-input single-output AWGN broadcast channel is considered . For a chosen index code and a arbitary mapping , a decision rule for the maximum-likelihood(ML) decoder is derived. The messsage error performance of a receiver at high signal-to-noise ratio (SNR) is charcterized by a parameter called PSK-index coding gain (PSk-ICG). The PSK-ICG of a receiver is determined by a metric called minimum inter-set distance.

- ### Wireless Biirectional relaying Using Physical Layer Network Coding With Heterogenous PSK Modulation

  In bidirectionak relaying using physical layer network coding (PLNC), it is generally assumed that users employ same modulation schemes in the multiple access phase . It may not be desirable for the users to always use the same modulation schemes , particularly when user-relay channels are not equally strong. Such a scheme is called heterogenous PLNC where users employ different modulation schemes .

- ### A Relation between Network Computation and Functional Index Coding Problems

  In contrast to the network coding problem, the sinks demand functions of the source messages. Similarly , in the functional index coding

problem, the side information and demands of the client includes disjoint sets of the messages , as is the case in the conventional index coding problem. it is known that any network coding problem can be transformed into an index coding problem and vice versa .
Here we show that any network computation problem exists if and only if a functional index code for a suitably constructed functional index coding problem exists.
we also show that a functional index coding problem admits a solution of a specified length if and only if a suitably constructed network computation problem admits a solution.

- **Optimal error Correcting Delivery Scheme For coded caching with Symmetric Batch Prefetching**

  Coded caching is used to reduce network congestion during peak hours. A single server is connected to a set of users through a shared bottle neck link, which generally is assumed to be error free.During non peak hours all the users have full access to the files and they fill their local cache with the portions of the file available.During deleivery phase each user requests a file and the server deleiver coded transmissions to meet the demand taking into consideration their cache contents .
  here we assume that a new delivery scheme is required to meet the demands of the each user event after the receving the finite number of errors in transmission. we chracterize the minimum average rate and minimum peak for this problem . we find closed form expressions of these rates for a particular caching schemes namely symmetric batch prefacing. we also propose an optimal error correcting deleivery scheme for coded caching problems with symmetric batch prefetching.

Research activities in this lab are guided by Prof. B Sundar Rajan.

8.5 Speech and Audio Signal Lab

Speech, Music and other Audio signals define and influence a large part of human cognitive experience. Speech/Music compression for communication/storage, automatic speech/music recognition/classification for manmachine interaction, speech/music enhancement in noise/interference/disability, multi-channel sound source localization and sound field rendering are type of problems that we address using the technologies of signal processing and pattern recognition, which is both exciting, challenging and rewarding.

These topics touch science at one end (perception/cognition) and technology products (robots) at the other end, with many intermediary solutions.

Research facilities in the speech and audio signal processing lab are guided by Prof. T V Sreenivas.

8.6 Statistical Signal processing Lab

As the lab name suggest this group works on the issues related to Statistical signal processing :space-time signal processing with application to wireless communication and acoustic signal separation. Areas of interest include:

+Signal Processing Algorithms for MIMO Wireless Communication +Signal Processing Algorithms for Wireless Sensor Networks +Compressed Sensing and Sparse Signal Processing +Position Location and Navigation for Indoor Enclosed Spaces +Assistive Technologies for Elderly.

Some research and project sone by Lab :

- **Wireless channel modelling of Drone to ground link in 2.4Ghz and 5Ghz Bands**

  use of Wifi systems on drones has not yielded satisfactory performance due to the doppler induced by the motion of drones. Wireless channel modelling of the drone to ground link would help us in designing new PHY and MAC layers for high-speeds links. The goal is also to look at communication between drones in an airbrone network of drones.
  In our project, we are trying to model this channel at 2.4Ghz and 5Ghz

bands by conducting experiments in different terrain like open spaces, wooded areas,multi-level housing blocks and heavy road traffic areas.In addition, we plan to measure the interference levels in the ubiquitous WiFi modems in the terrains we consider.//

A known signal is modulated and sent from the drone .The ground based receiver obtaines the received signal and estimates the channel and doppler spectrum.

- **Optimal subarray Design for Adaptive Jammer Suppression in Phased Array Radars**

  * Given the implementation challenges ,Digital Beam Forming (DBF) at element level is not practical for larger phased array radars.
  * First analog beamforming is done to make into subarrays,then the subarray outputs are down converted and digitized for further processing . * The sub array layout has a strong impact on the performance on the Array Signal processing.
  * The subarray layout has a strong impact on the performance of the Array Signal Processing (ASP) algorithms performed at the sub array level.
  * Enhance the detection and tracking performance of existing regular subarray based phased array radars (with only DBF),in adverse jamming scenario using Adaptive Beam Forming(ABF) by suppressing jammer signal.
  * Reduce the computational load in large phased array radar with element or subarray level digitization by making optimal digital subarrays for ABF .

This research group is guided by Prof. K V S Hari. Mr. M K Ravishankar is associated with the lab.

8.7 Wireless Research Lab

This research group works on the issues in wireless communications such as: DS-CDMA, multi user detection, fading and diversity, space-time codes and wireless networks and protocols : energy efficient communications, ad-hoc and sensor networks.

Research in this lab guided by Prof. A. Chockalingam.

8.8 Applied Photonics Lab

Research activities in applied photonics labs spans in the areas of Integrated optics - application to WDM optical networks and microsensor sytems; photonic bandgap structures, MOEMS, Integrated optic devices and characterization; Fiberbragg grating Sensors, WDM Optical Netowrks; Spatio-temporal codes for fiber-optic CDMA networks, Microsensor technology; biomedical applications.

some projects and research done by lab :

- **Two dimensional Optical Orthogonal Codes for Fiber-Optic CDMA Networks**
- **Quality-of-Transmission-Aware Manycasting Over Optical burst-switched Networks**
- **Optical Amplification and Photosenstivity in Sol-Gel Based Waveguides**

Prof. SrinivasTalabatulla, Dr. T Badrinarayana, Dr. E S Shivaleela, K Elizabeth Rani are actively associated with the research activities of applied photonics lab.

8.9 Microwave Lab

The emphasis research of the Microwave Laboratory is on developing miniaturized and efficient components and subsystems for current and future applications in the extended radio frequency spectrum, making use of advancements in micromachining, micro-electromechanical systems, materials science and computational electromagnetics.

In areas of microwave imaging and antennas, we are investigating ultra-wideband systems. in microwave and RF circuits involves techniques for generation of chirped pulses and studies on their propagation parameters. We are utilizing Si based microfabrication facilities to build vacuum tube devices like folded waveguide traveling wave tubes for sub-mm and THz frequencies.

In the computational domain, our work involves techniques for solving Maxwell's equations.

some research and projects done by lab :

- **Coplanar Capacitively Coupled probe Fed Microstrip Antennas For Wideband Applications .**

  The design and analysis of a co planar capacitive fed microstrip antenna suspended above the ground plane is presented.It is demonstrated that the proposed approach can be used designing antennas with impedance bandwidth of about 50% and a good gain to operate in various microwave bands . The model of antenna incorporates the capacitive feed strip which is fed by a coaxial probe using equivalent circuit approach, and matches and experimental results.The capacitive strip used here is basically a rectangular microstrip capacitor from a truncated microstrip transmission line and all its open ends are represented by terminal or edge capacitances . The error analysis was carried out for validity of the model for different design parameters . The antenna configuration can be used where uni-directional radiation patterns are required over a wide bandwidth .

- **Dual-frequency chracterstics of Minkowski-square ring antennas.**

  Fractal Minkowski curves to design a compact dual - frequency microstrip ring antenna are proposed .Slides of a square ring have been selectively replaced with first and second iterations of the generalised fractal geometery to design a smaller antenna with dual frequency operation . This behaviour has been explained based on current distributions on the antenna structure . Measured results compare well with electromagnetic simulations .

- **Multi-port Network Approach for the analysis of Dual Band Fractal Microstrip Antennas .**

  The multiport network approach is extended to analyze the behaviour of microstrip microstrip fractal antennas.The capacitively fed microstrip square ring antennas has the side opposite ti the feed arm replaces with a fractal Minkowski geometery . Dual frequency operation is acheived by suitably choosing the indentation of this fractal geometery . The width of two sides adjacent to this is increased to further control the resonant characterstics and the ratio of the two resonance frequency of the antenna . The impedance matrix for the multiport network model of this antenna is simplified exploiting self-similarity of the geometery with greater accuracy and reduced analysis time . Experimentally validated results confirm utility of the approach in analyzing the input characterstics of similar multi-frequency fractal microstrips antennas with other fractal geometrics.

8.10 Signal Processing and Communication lab

As the name of the lab suggests, we are interested in the areas of digital signal processing, information theory, estimation theory, and their applications in the optimization of (mainly, wireless) communication systems. Current research spans a range of topics including MIMO communications with channel state feedback, channel estimation and joint channel estimation and data detection, cognitive radio, energy harvesting communications, compressive sensing and sparse Bayesian learning, scheduling and interference management in wireless networks.

Research activities in the signal processing for communication lab are guided by Dr. Chandra R. Murthy.

8.11 Optics,Nanostructures and Quantum Fluids Lab

We have wide interests in studying light-matter interactions in novel nanoscale systems, ranging from electron bubbles in superfluid helium to helical nanoplasmonic devices, and magnetic nano-propellers.

Research in our group is focused on three apparently different nanoscale systems, ranging from nanometer sized bubbles containing single electrons in superfluid helium to a three dimensional array of plasmonic nanoparticles and magnetically actuated helical nanostructures. The experimental techniques used to probe these systems are similar in nature, relying on simple physical probes based on optics (spectroscopy), acoustic and hydrodynamics. The helical and plasmonic nanostructures are the building blocks of an integrated intelligent nano-system, and thus contribute towards achieving the same bigger research goal.

Research in this is guided by Dr. Ambrish Ghosh.

8.12 Analog and RF system Lab

Analog and Radio Frequency integrated circuits make up a significant part of the global semiconductor market today. While these circuits have enabled the telecommunication and wireless revolutions in the last decade, ever increasing demand for bandwidth and spectrum is leading to new methods of optimizing the usage of the RF spectrum. In our group, we are currently working on two such areas - integrated cognitive radios and millimeter-wave radios. We are also working on analog and RF sensors and various methods of using them in distributed sensor networks, using low power radio transceivers. Such distributed sensors are expected to play a major role in building cyber-physical systems, for use in agriculture, healthcare, energy, and transportation.

Currently working on :
Analog and RF system lab is currently working on the **RADARS** with the use of **FMCW(Frequency Modulated Continuous Wave)**

It will use the frequency of 2Ghz to 4Ghz.

It will help in **through the wall communication** which will later on help in **medical sciences and Networks .**

Research activities in the Analog and RF system lab are guided by Dr. Gaurab Banarjee.

8.13 Numerics of Integrated Circuits and Electromagnetics (NICE)

Numerics of Integrated Circuits and Electromagnetics (NICE) laboratory focuses on numerical formulation and algorithm development towards capturing the physics of circuit and electromagnetic effects. Consolidating our analysis framework, we venture into the world of automated design and synthesis of chip-package-systems under the umbrella of Electronic Design Automation (EDA) or Computer-Aided Design (CAD). We like high-speed communication channels, power-ground networks, through-silicon-vias, antennas to name a few. We think RF imaging is a powerful underutilized sensor. We are into cloud and mobile computing. We agree - the concept of "compute-power for all" aided by the cloud and "accessed-from-anywhere" aided by the mobile personal device is awesome! Our motto is to "BE NICE".

Research activities in this lab are guided by Dr. Dipanjan Gope.

8.14 WiCOM Lab

Wicomnet Lab was established in 2004 as a central facility in the Department. Current areas of research in this lab are wireless sensor networks, organizational network analysis, and cognitive radio.

Incharge of this lab are Mr. S V Gopalaiah.

9 CDS (Computational data science)

CDS is engaged in cutting-edge research programs in areas relating to computational and data science, computing and data systems, and their applications. The research focus of CDS is broadly classified into Computer Systems and Computational Science, that include data science and engineering, with sub-areas within each:

9.1 Computer and Data Systems Stream (CDS-CS)

- **Computer Architecture & High Performance Computing**
  - System on Chip and Embedded Processor Architectures, High Performance Computing, Runtime Reconfigurable System-on-Chip (SoC) architectures, modeling of massively parallel reconfigurable silicon cores, compilation techniques for reconfigurable silicon cores, large scale simulations on massively parallel and distributed SoC architectures, application synthesis on Runtime Reconfigurable SoCs
  - Labs : Computer Aided Design Lab
- **Software & Runtime Systems**
  - Compiler Optimization, Runtime Frameworks, Middleware for Batch Systems, Cloud computing
  - Labs:
    1. Middleware and Runtime Systems (MARS) Lab 2. Distributed Research on Emerging applications and Machines (DREAM) Lab
- **Data Management, Computing & Analytics**
  - Database Systems, Big Data Analytics & Platforms, Computer Vision, Distributed Data Systems, Machine Learning and Natural Language Processing
  - Labs:
    1. Database Systems Lab
    2. Video Analytics Lab
    3. Visual Computing Lab
    4. Machine And Language Learning (MALL) Lab
    5. Distributed Research on Emerging applications and Machines (DREAM) Lab

9.2 Computational Science Stream (CDS-CP)

- **Computational Science and Engineering**
  - Modeling, Computational Mathematics, Mathematical Software/Libraries, Parallel Computing

- * **Computational and Statistical Physics Lab (CSPL)**

  Numerical Linear Algebra, Photonics, Condensed matter, Computational and Statistical Methods.
- * **Computational Mathematics Group (CMG)**

  Finite Element Analysis, Finite Element methods for the solution of PDEs and surface PDEs, High Performance Computing, Modeling of Multiphase Flows, Modeling of turbulent flows with moving/deforming solid bodies, Moving contact line problems, ParMooN, an OpenMP and MPI based hybrid parallel finite element software
- * **Medical Imaging Group (MIG)**

  Computational methods in medical imaging, multi-modal imaging, medical image reconstruction techniques, diffuse optical tomography, photo-acoustic imaging, neuroimaging
- * **Scientific Computation Lab (SCL)**

  Control and Optimization of Constrained Dynamical Systems, Stochastic and Deterministic Differential-algebraic equation systems, Mathematical Libraries, VLSI CAD applications

- **Bioinformatics**
  - Computational genomics, Structural bioinformatics, Systems Biology, Drug and Vaccine Discovery, Bioinformatic Databases and Software Tools
  - Labs:
    1. Structural Biology and Bio-computing Lab 2. Biomolecular Computation Lab

Conclusion

In conclusion, it is evident that 4G technologies will expand on web-based communications around the world. 4G technology will allow for improved applications such as telemedicine that may save lives. It is a fully IP-based network and will improve data transfer dramatically. Signal disruptions will be minimal and downloads will be done in a matter of seconds, faster than ever before. In the near future, a 5G cell phone will be created along with a 5G network based on 4G technologies allowing for the world to connect limitlessly.

In future we can use the 5G technology, Many big countries are investing huge amount of money on this project as it was having high demand in the future. It will altogether manufacture flexibility, limit, degree, comparability and meeting. Thusly, it will satisfy the growing solicitations of rising bigdata, cloud, machinetomachine, and diverse applications.

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