

**Tools and Techniques for Heterogeneous Wireless Networks
Coexistence**

A Dissertation Presented

by

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To everyone.

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Abstract of the Dissertation

Tools and Techniques for Heterogeneous Wireless Networks Coexistence

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Prof. Lorenzo Favalli, Adviser

The world has become interconnected like never before, in diverse and complex ways and his diversity and complexity doesn't seem to slow down. The increasing demand for higher network capacity and new applications and network presence is putting more pressure on even more growth and interconnection of existing network technologies and toward the research and development of new versatile network architectures that embrace heterogeneity and pervasiveness as an initial design paradigm.

This surge in scale and complexity, plus the proliferation of heterogeneous wireless networks, challenges network researchers to come with novel techniques and methodologies that can achieve affordable, credible and reproducible results, for the development and experimentation with the various network architectures and communications protocols involved. It also brings complex challenges that reflect the complexity and diversity of the involved Wireless Networks technologies. For instance we show that LTE/WiFi coexistence problem associated with the current interest in providing unlicensed band access ability LTE networks , is an example of a problem where current research has been dealing with such challenges like Interference management, heterogeneous networks coexistence, and resource allocation.

The work conducted as part of this dissertation is with the goal to tackle two main research problems. First, we set to develop a novel Simulation/Emulation framework for enabling large scale and flexible studies of Cognitive/Heterogeneous Wireless Networks and their related characteristics. This framework provides an environment for creative and flexible research experimentation using modern simulation technique.

Second, we examined the problem of LTE/WiFi Coexistence as a current example of a complex Heterogeneous Wireless Networks Coexistence problem, and we proposed a novel algorithm that tackles this issue after a detailed review of the proposed solutions and understating of

both systems behavior in a coexistence environment. This work was accompanied with a testbed build to allow real validation of coexistence mechanisms, combined with accurate simulation tools that provide relative accuracy from Physical Layer up to the Network Layer.

Chapter 1

Introduction

A continuous growth of the demand for higher data rates in recent years is going side by side with a tremendous growth of wireless network technologies and their related devices, protocols, and applications to satisfy the demand. This continuous surge has already produced a never seen before segmentation of wireless technologies caused by independent endeavors led divert visions and separate efforts to meet different user profiles and Spectrum Management policies. This can be excellently exemplified by the evolution paths of two major standardization efforts, mainly IEEE 802.11 and 3GPP mobile networks standards, which can be visualized in Figure 1.1 and Table 1.1 respectively.

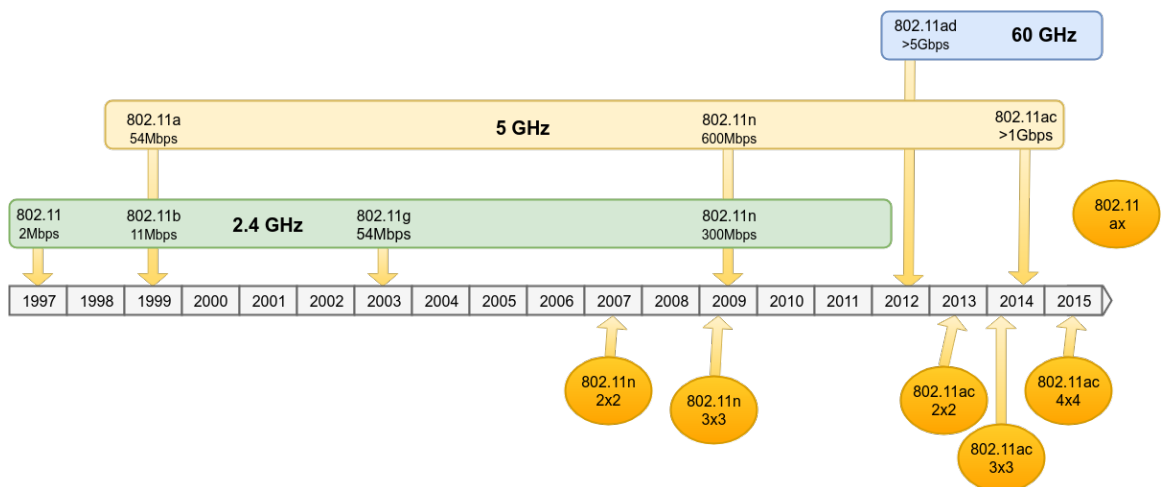


Figure 1.1: Evolution of 802.11 standards

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Table 1.1: Evolution of Mobile Communication Networks

Generations	Access Technology	Data Rate	Frequency Band	Bandwidth	Forward Error Correction	Switching	Applications	
1G	Frequency Division Multiple Access (FDMA)	2.4 Kbps	800 MHz	30 KHz	NA	Circuit	Voice	
2G	Time Division Multiple Access (TDMA)	10 kbps	850/900/1800 /1900 MHz	200 KHz			Turbo Codes	Packet
	Code Division Multiple Access (GPRS)			1.25 MHz				
2.5G	General Packet Radio Service (GPRS)	50 kbps		200 KHz				
	Enhanced Data Rate for GSM Evolution (EDGE)	200 kbps						
3G	Wideband Code Division Multiple Access (WCDMA)	384 kbps	800/850/900/ 1800/1900/2100 MHz	5 MHz	Turbo Codes	Packet	Voice + Data + Video	
	Code Division Multiple Access (CDMA) 2000			1.25 MHz				
3.5G	High Speed Uplink/Downlink Packet Access (HSUPA/HSDPA)	5-30 Mbps		5 MHz				
	Evolution Data Optimized (EVDO)			1.25 MHz				
3.75G	Long Term Evolution (LTE) Orthogonal/Single Carrier Frequency Division Multiple Access (OFDMA/SC-FDMA)	100-200 Mbps	1.8/2.6 GHz	1.4MHz to 20 MHz	Concatenated Codes	Packet	Online gaming + High Definition Streaming	
	Worldwide Interoperability for Microwave Access (fixed WIMAX) Scalable Orthogonal Frequency Division Multiple Access (SOFDMA)		3.5/5.8 GHz	3.5/7 MHz in 3.5GHz band 10MHz in 5.8GHz band				
4G	LTE-Advanced OFDMA/SC-FDMA	DL 3Gbps UL 1.5Gbps	1.8/2.6 GHz	1.4MHz to 20 MHz	Turbo Codes	Packet	Ultra High Definition Video + Virtual Reality	
	Mobile WIMAX	100-200 Mbps	2.3/2.5/3.5 GHz	3.5/7/5/10/8.75 MHz				
5G	Beam Division Multiple Access (BDMA) and non/quadi orthogonal or Filter Bank Multi-Carrier (FBMC) Multiple Access	10-50 Gbps	1.8/2.6 GHz 30-300 GHz	60 GHz	Low Density Parity Check Codes (LDPC)	Packet		

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Since the first release of 802.11 standard in 1997, with a maximum data rate of 2Mbps, the standard has been continuously enhanced. The 802.11a and 802.11b standards were created in 1999. 802.11b came to boost WLAN technology into widespread use and be considered the first generation of Wireless Local Area Network technology. It had a maximum data rate of 11Mbps, it was soon superseded by the second generation of WLANS, the 802.11a standard. Which, for the first time, accessed the 5GHz band and achieve a data rate of 54 Mbps. IEEE 802.11g is considered the third generation, it reached 54 Mbps while still used the 2.4GHz channel. In 2005 IEEE released 802.11e that was intended as an enhancement to 802.11/b/a, it came with additional Quality of Service (QoS) features, with data type-based priorities for data, talk and video transmissions, plus it operated at frequencies of up to 5.850. In 2007, 802.11n was released as the fourth generation, it broke the data rate record by achieving 450 Mbps, it also operated on both 2.4GHz and 5GHz bands. 802.11n was upgraded in 2009 to reach 600Mbps of data rate.

The evolution kept going on, 802.11v, 802.11u and 802.11k were subsequently designed to improve network-wide traffic distribution in WLAN networks, as a consequence of the high densification of WLAN deployments that emerged. The gigabit Wi-Fi (Also know as 802.11ac) came to light in 2013 as the fifth generation of WLAN technology. It achieved a much higher data rate of 1.3 Gbps and supported exclusively the 5GHz band. It was soon updated in 2014 by the release of a second version, this time it came with 6.93 Gbps of potential data rate, implementing Multiple Input, Multiple Output (MIMO) technology, thus enabling devices to send multiple streams to multiple clients simultaneously. It supported a channel width of 160MHz, that could give application that demand high throughput an exclusive pathway, thus further improving performance. Currently 802.11ad uses millimeter wave technology (mmWave) on the 60GHz band instead of the 5GHz and 2.4Ghz used up till now. It thus boasts a potential maximum data rate of 7Gbps. 802.11ad operates in a limited range, as a consequence of operating in the 60GHz band, but the extremely higher data rate it offers enables wide range of new applications WLAN networks, ranging from virtual reality, multi-device streaming using PCs, tablets, phones ...etc, and dealing with high definition and ultra high definition files, 4K footage and raw multimedia files, all at the office or home. The latest 802.11 standard is the 802.11ax, which also brings features suitable for dense deployment scenarios. With 8x8 Multi User MIMO (MU-MIMO) and OFDMA access technology, it also brings a new medium access approach that combines CSMA/CA traditionally being using as WiFi's access mechanism

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of choice, with an uplink resource scheduler, and other resources scheduling and energy efficiency features.

Mobile communications systems also witnessed a long path of evolution in terms of how it started and what it became. The first generation of cellular networks (1G) from the 1980s were analog, operated in the 800 MHz band and could only handle voice at data rates as low as 2.4 Kbps. Second generation networks came in the 1990s, adopting a new Global System for Mobile Communications (GSM) standard, and moved on the digital instead of analog transmission. 2G GSM networks basically led to explosive proliferation of mobile phone usage, that kept rising up till now, it introduced new features such as Short Short Message Service (SMS), plus reduced battery usage for mobile phones, better voice clarity as a consequence of using digital transmission.

2.5G networks used General Packet Radio Service (GPRS) technology. GPRS proved data rates ranging from 56 kbit/s to 115 kbit/s. It introduced Wireless Application Protocol (WAP), Multimedia Messaging Service (MMS) and internet communication services (email and World Wide Web). Enhanced Data Rates for GSM Evolution (EDGE) was created as an extension for GSM and considered as the 2.75G network, it provided clear voice communication and faster data transmission of up to 384kbit/s.

3G networks advanced more high speeds and a new IP data network for mobile communications, it built on the widespread usage launched by 2G networks, that lead to rising demand for higher data rates that could not be achieved by 2G technologies. Thus packet switching finally was adopted side by side with the traditionally circuit-switched networking, the first for high speed data communication and the latter for voice communication. 3G networks, boosted a new transformation in how mobile networks are used, its higher data rates allowed new applications ranging from video stream of radio to television on mobile handsets. 3G evolved in mid-2000s towards High-Speed Downlink Packet Access (HSDPA) (termed 3.5G, 3G+ or turbo 3G). HSDPA allowed higher data transfer speeds and capacity, with downlink speeds from 1.8 to 14 Mbps, with HSPA+ this could achieve 42 Mbps or even 84 Mbps with 3GPP release 9 standard.

Mobile broadband reached a new realm with 4G, with speed improvements reached 10-fold over previous generation. It expanded high definition audio/video streaming of an IP based network. Long Term Evolution LTE 4G networks could boast data speeds of 100 Mbps for the downlink and 50 Mbps for the uplink, while LTE-Advanced could reach up to 1 Gbps.

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LTE and LTE-A aspires to satisfy the needs of operators and mobile users in a much more heterogeneous way. Different types of users exhibit different utilization patterns, thus different modes of operation are needed, and an accommodation to the already available technologies should be taken into account. Carrier Aggregation (CA) and Coordinated Multipoint (CoMP) are the basic enablers of what could be called Heterogeneous Networking in LTE, CA allows the allocation of dispersed spectrum bands to provide a higher overall bandwidth while CoMP improves transmission coverage at cell edges by dynamically coordinating between different base stations to increase network coverage within any given cell. Another solution to increase coverage and network capacity is densification of macro-eNB deployments within the network, however that could be problematic from logistics and cost-effectiveness point of view especially in urban areas. A better approach would be deploying low-power stations and relays to existing macro-eNB. Thus small cells are created to satisfy high peak traffic spots on demand, in a cheap and flexible way. Inter-cell Interference Coordination (ICIC) is a key enabler to deal with the potential increase in network density thus increase in inter-cell interference inside a network, combined with CA and CoMP, HetNet are becoming a solid design choice with LTE deployments.

Always in the context of evolution towards next Mobile Networks Generations, LTE currently is evolving toward 5G mobile networks, with new design requirements and much more ambitious goals. It aspires to support the explosive growth of data traffic, support for massive numbers of machine type communication devices (MTC), mission critical low latency communications. Support of mmWave communications in the 100GHz band in combination with current cellular bands from 600 MHz to 3.5 GHz plus access to the unlicensed 5GHz bands.

Rel-13 for instance introduced major enhancements of spectral efficiency and full dimension MIMO (FD-MIMO), this should drastically boost efficiency through the deployment of large number of antennas at the base station. It introduced Licensed Assisted Access (LAA), to enable the utilization of unlicensed spectrum in the downlink, while maintaining a fair coexistence with 802.11 devices by exploiting enhanced Carrier Aggregation (eCA).

This situation inspired new methodologies and tools to assist in bypassing the segmentation threat to future evolution. New technologies such as LTE HetNet architecture provides a more integrated approach towards service delivery by combining traditional cellular architecture in mobile networks with the flexible random architecture of WLAN technologies. Other technolo-

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gies such as LTE-Unlicensed, take a different yet complimentary approach by allowing traditional license-based spectrum access to be enhanced by accessing the industrial, scientific and medical (ISM) and the Unlicensed National Information Infrastructure (U-NII) radio bands; in order to take advantage of the free nature of these bands and the potential considerable increase in network capacity. Other concepts such as Cognitive Radio proved very influential by inspiring the research and development of advanced Spectrum Sensing and Dynamic Spectrum Access Techniques that proved to be relevant and applicable to a wide range of Wireless Networks situations and also motivated the development of new Software-Defined Radios (SDRs).

1.1 Research Challenges

This complex landscape of Wireless Networks Technologies poses new complex challenges for the research community and regulators on different levels. The aforementioned new techniques need to be accompanied with not only novel interference management techniques, co-existence solutions, better energy consumption ... etc, but also new experimentation tools, testbeds and simulators.

When it comes to Networks Simulations, good network components modeling has a tremendous effect on the overall accuracy of simulation results. More importantly, it has been long known that protocol specification-compliance in simulation models and Physical Layer accuracy have a substantial effect on the credibility of achieved simulation results [15, 42]. These considerations become even more relevant and important to the current state of complex network architectures, cross-layer protocol designs and new waveforms, frequency bands and spectrum access techniques.

As we will describe later, various simulation tools were developed along the evolution of wireless networks, tools that satisfy different needs in terms of scope (Physical layer vs Network Layer). We argue in this thesis that when it comes to the study of modern heterogeneous topologies and Cognitive/Dynamic Spectrum Access Networks, the available simulation tools lack the necessary adaptation to the specificities of current research and are limited in their offerings of mature frameworks. They do not provide integrated environments to tackle the major issues of modern networks, for instance mass deployments associated effects (Scalability) and the more relevant than

before effect of accurate enough physical layer simulation on modern cross-layer protocols. Thus we took the task to tackle this research issue and attempt to provide a modern, capable simulation framework for Cognitive/Heterogeneous Wireless Networks based on the NS-3 opensource project and a new combined detailed network level simulation with accurate physical layer emulation as an integration of NS-3 and Matlab LTE System toolbox.

Another research problem relevant to the status-quo of wireless networks can be exemplified in the hot-topic LTE/WiFi coexistence problem. A complex yet very luring challenge to both academia and industry, considering the potential benefits that could be achieved by providing viable coexistence solutions. We considered this research problem as another related goal for this PhD and we worked to propose a novel coexistence method based on network clustering and graph theory optimization supported by networks simulations and off-the-shelf experimental testbed built specifically for LTE/WiFi coexistence scenarios, all this shall be defined later on.

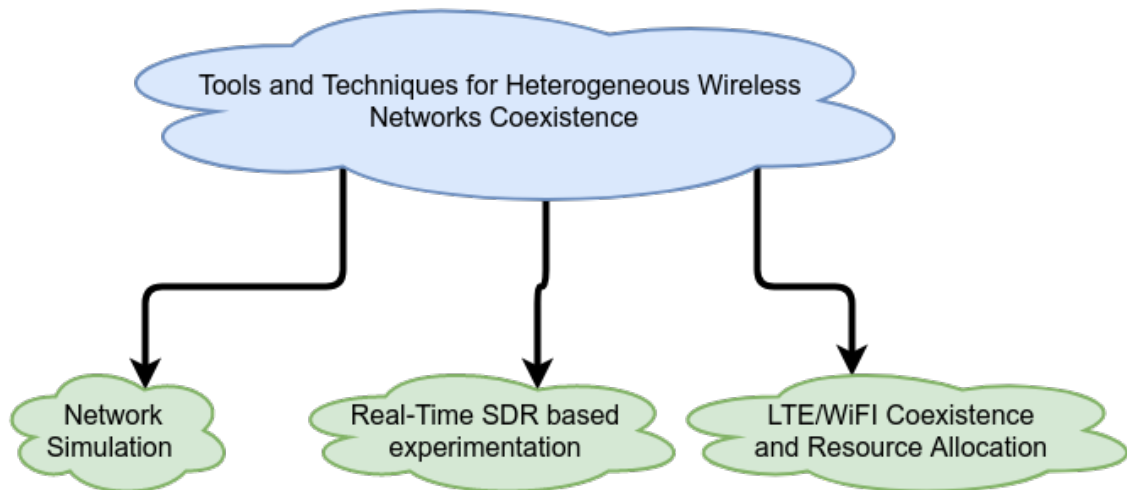


Figure 1.2: Research Challenges

1.2 Organization

The aforementioned research challenges and proposals tackled in this PhD work are depicted in Figure 1.2. First after this introduction, in Chapter 2, I outline the research context and various terms plus the status quo of relevant technologies related to my research work.

In Chapter 3, I motivate and introduce a novel simulation architecture for the problem

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under the scope of Cognitive/Heterogeneous Wireless Networks Simulations/Studies. Finally in Chapter 4, I move on to describe an effort in proposing a novel solution to LTE/WiFi coexistence problem termed E-Fi (Evasive WiFi). E-Fi defines a new WiFi evasive behavior that adapts to LTE interference and intelligently exploits LTE characteristics (Almost Blank Subframes) and new WiFi features (WiFi-Direct) combined with a clustering algorithm and a resource allocation optimization algorithm based on the Hungarian algorithm. In the end, we conclude the thesis and define future research goals and eventual developments for the current work.

Chapter 2

Heterogeneous Wireless Networks

Heterogeneous Wireless Networks is a concept emerged to describe the reality of a world with high proliferation of Wireless Networks technologies. Technologies with continuous and fast evolution driven by various utilizations needs. Plus the convergence/intersection in the services that various wireless technologies traditionally provided separately. Thus Heterogeneous Wireless Networks also describes the evolution of such technologies in the direction of a multi-networking infrastructure broadband information access to satisfy the need for ubiquity demanded by current usage patterns of various communications services, multimedia, and other network-dependent applications. The landscape of currently widely deployed Broadband Wireless Access technologies include for example:

- Worldwide Interoperability for Microwave Access (WiMAX).
- Enhanced Data Rate for Global Evolution (EDGE).
- Bluetooth.
- Wide Code Division Multiple Access (WCDMA).
- wireless local area networks (WLAN) such as 802.11 set of technologies.

The characteristics of many of these technologies are complementary in many aspects even-though they might operate at very different levels of scale and architectural organization. With

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that said the idea of a Heterogeneous network that adapts to various scales of operation and combines characteristics of Wide Area Networks (WAN) down to Local Area Networks (LAN). In addition to other emerging technologies such as IoT, mmWave communications ...etc, is a serious research endeavor as can be seen both in academia[1, 38] and industry[43, 16, 51] alike, where an ideal picture of a future Heterogeneous Network might look like Figure 2.1

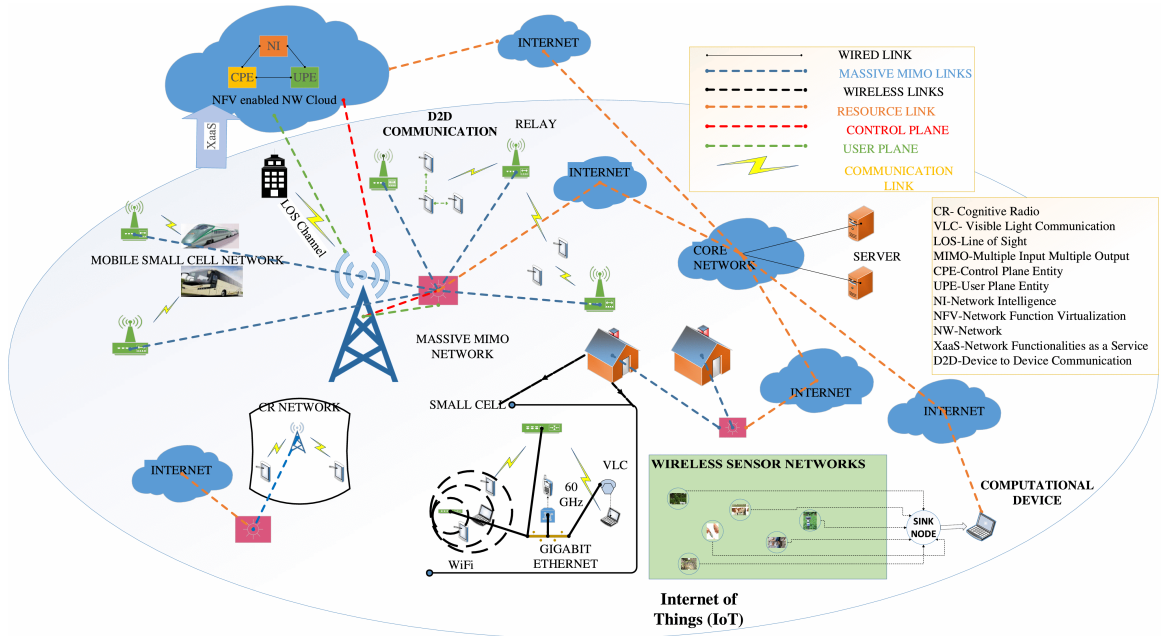


Figure 2.1: A general 5G cellular network architecture[38]

2.1 HetNet in Mobile Communication Systems

Current WLAN networks (802.11b/g/a/n/ac) can attain high data rates in the orders of tens to hundreds of Megabits per second, but they are (and historically has been) constrained in the coverage area they are capable of serving. On the other hand we find Cellular mobile systems systems; which historically traded a Wide Coverage area capability for a low data rate and poor support for data traffic. This is not the case anymore for current systems such as Long Term Evolution (LTE) for which provide traditional capabilities such as wide full mobility, coverage areas, and roaming while offering high data rates for all types of traffic.

LTE, for instance, is a prime example of Cellular networks evolving from old Circuit-Switched Networks to a Packet-Switched Network operation which years before was mainly the

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domain of WLANs to opt for IP-Based communications. At the same time, there is a high proliferation of WiFi hotspots with many examples of high-density deployments in urban areas offering seamless roaming and mobility handling with high data rates. The current situation is in such a way that WLAN deployments complement/enhance Cellular networks deployments by providing cheaper, faster and more flexible Broadband access technology in areas or situation where a Cellular Deployment would not be the optimal choice.

Other differentiating aspects of WLAN and Mobile Communication Networks are the term on which they are developed and the challenge that puts on grouping them in a HetNet architecture. For example, 802.11 in one hand operates in unlicensed bands thus assumes no mandatory prior coordination or network wide scheduling of various Network Components (Stations and Access Points). As a consequence, the Medium Access Protocol reflects this reality and implements a Distributed Coordination Function (DCF) based on a Carrier Sense Multiple Access with Collision Avoidance protocol (CSMA/CA). In this mode of operation 802.11 nodes contend for access and looks for transmission opportunities that avoid interference from other nodes. LTE operates differently, an LTE network operator assumes exclusive access to the band of interest; as a result, the network operation is totally scheduled with a completely different network architecture.

Researchers have predicted the possible explosion in the number of mobile device usage and base stations within a not too distant future. However, continuously adding traditional macro cell base stations into network raises many new challenges and modifications. One possible solution is to adopt WiFi access points and a new heterogeneous topology is proposed correspondingly.

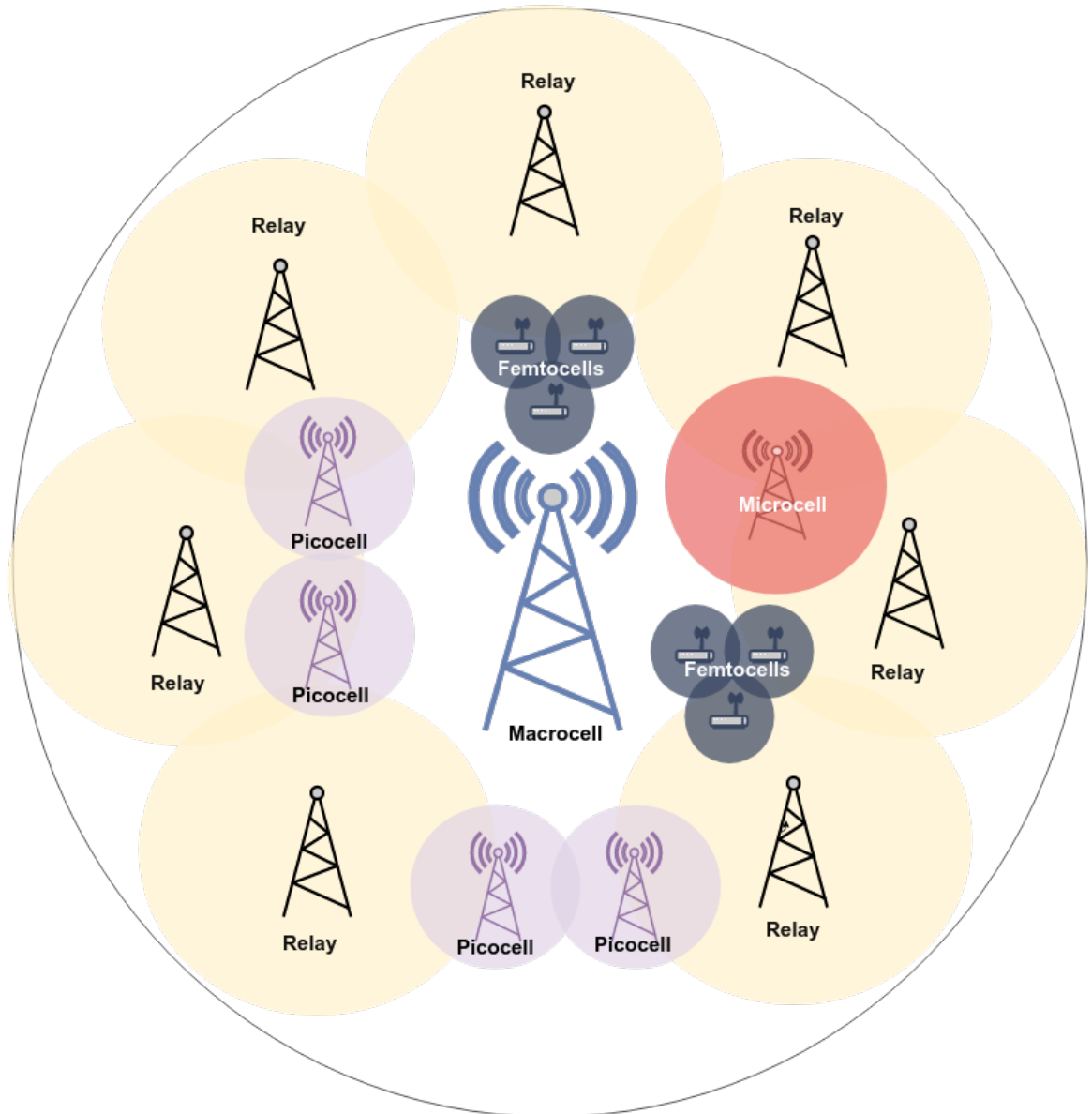


Figure 2.2: LTE HetNet Architecture

With all that said, HetNets emerged as a up-and-coming technology for satisfying specifications drawn for LTE and LTE-Advanced. Figure 2.2 outlines the architecture of HetNet topology within LTE. Several new concepts of access technologies are defined, coordinating together to enable said HetNet architecture, mainly Femtocell and Picocell node types which are added to 3GPP set of standards next to the existing Macro/Microcell, Relay and RRH types, a list of these nodes and their characteristics is depicted in Table 2.1 where:

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Table 2.1: Characteristics of several types of nodes in heterogeneous networks [78]

Type of nodes	Transmit power (dBm)	Coverage	Backhaul
Macrocell	46	Few km	S1 Interface
Picocell	23-30	<1300 m	x2 Interface
Femtocell	<23	<50 m	Internet IP
Relay	30	300 m	Wireless
RRH	46	Few km	Fiber

- **Femtocell:** They play a similar role to that of a WiF AP, in terms of throughput, coverage, and bandwidth used. They are usually deployed without centralized planning connected also in a similar way as a WiFi AP with a backhaul being a broadband internet access provider.
- **Picocell:** Are deployed by operators and aim more toward a more stable Quality of Service than Femtocells with higher quality backhauls installed and maintained by the operator.

LTE HetNets bring a set of new functionalities, for instance, performance metric shifts from outage/coverage probability distribution (in terms of BER or SINR) and spectral efficiency (bps/Hz) to rate distribution and area spectral efficiency ($bps/Hz/m^2$). Plus, instead of the hexagonal grid that Base Stations (BSs) are placed within, HetNets small cells (pico/femto) are placed nested within these BSs and could even be deployed randomly (especially in the case of femtocells). In HetNets, users choose to connect to BSs that provide higher data rates rather than signal strength while possibly exhibiting different SINRs for the Uplink and Downlink [8].

The challenges specific to this new HetNet topology could be seen for example in mobility, backhaul link capacity and interference management. In HetNets users will probably deal with too frequent handoffs and dropped calls in cases of high mobility when connecting with small cells, and the small cells BSs will not have high speed connection to the core network as for macro cells which will constitute a performance bottleneck, plus the new dense HetNet deployment will be dealing with high levels of inter-cell interference which has to be dealt with by very efficient resource allocation mechanisms [8].

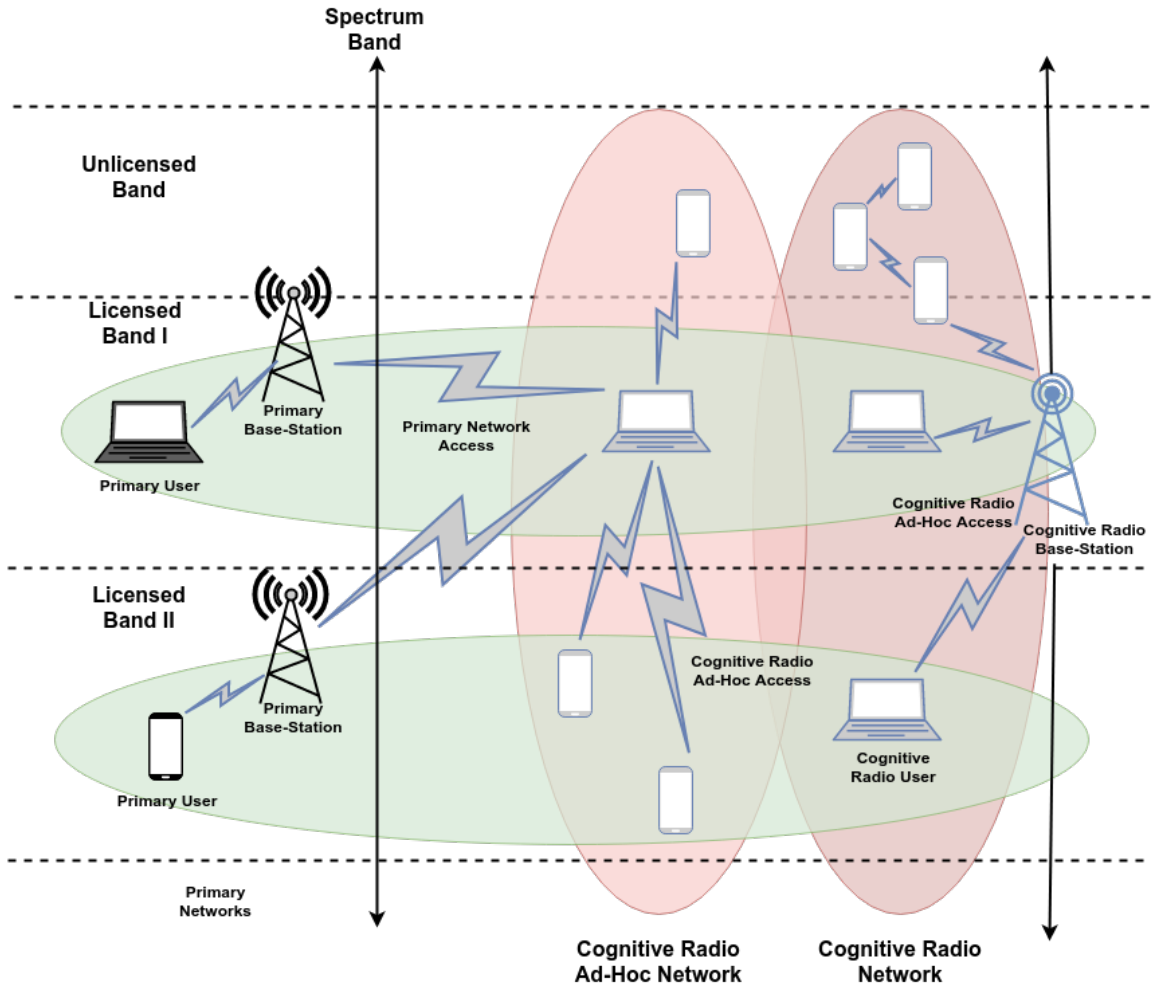


Figure 2.3: Cognitive Radio Networks Architecture[32]

2.2 Cognitive Radio Networks and Dynamic Spectrum Access

The continuous growth of the demand for higher data rates and new applications using Wireless Communication Networks is putting pressure like never before on traditional Spectrum Management policies, a limited resource that it is. Historically spectrum access is managed through state agencies that issue licenses to network operators defining the distinct bands they are allowed to deploy their wireless networks on. This process of license assignment and Spectrum Access restrictions goes a long way back with early Wireless Networks Technologies, but Wireless Technologies advanced tremendously and current networks much higher spectral efficiencies and better spectrum utilization. Which left us in a state where right now a huge portion is of the spectrum is not exploited while being sparsely distributed both in location, time and frequency.

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Cognitive Radio (CR) emerged as a concept in 1999 [61] when Joe Mitola and Gerald Maguire introduced it. Since then CR has been defined as a radio that adapts to the environment in which it operates by adjusting its transmission parameters. The radio also coordinates medium access with other spectrum users and/or employ spectrum sensing decision making for the same purpose[26]. Software Defined Radios SDRs emerged as a technology that provides the functionalities as mentioned above of Spectrum Sensing and transmission parameters reconfiguration.

In a licensed band a CR node operates as a secondary user (SU), it is allowed to access the spectrum opportunistically by looking for spectrum holes, this naturally increases spectrum utilization but needs the implementation of a spectrum detection ability. This to allow spectrum utilization at a lower priority and without harmful interference to Primary Users (PU) that are licensed to use the spectrum.

Figure 2.4 depicts the cognitive cycle that characterizes a cognitive radio and its capabilities, which can be summarized as the ability to sense, analyze and make decisions regarding spectrum access.

2.2.1 Spectrum Sensing

Spectrum Sensing is essential in enabling a CR node an understanding of the RF environment and potential primary user presence in the spectrum. The main objective of Spectrum Sensing is the detection of Spectrum Holes, which are part of the spectrum that falls within gray or white spaces according to the distinction established in [22]. Basically, gray spaces are the parts of the spectrum occupied by low power interferers, while white spaces are empty parts (except for ambient noise). Database aided spectrum access can be actually considered a form of Passive Spectrum Sensing, on the other hand what is called Active Spectrum Sensing is the direct interaction of the CR node with the RF medium to sense for RF activity. In [12, 84] good summaries of investigated and developed Spectrum Sensing techniques is provided. Also in Table 2.2 is provided a comparative list of various techniques for Primary User detection in CR Networks.

The main challenges for an efficient and accurate spectrum sensing is in the technique's susceptibility to harmful and performance degrading effects of various RF related phenomena, such as shadowing, circuitry induced uncertainty and multi-path fading.

Table 2.2: Spectrum Sensing Techniques

Detection Algorithm	Description of algorithm	What is modeled?	To what gain?
Energy detection	Get empirical estimate of energy in a frequency band and compare against a detection threshold.	Average power	Baseline detector for comparison
FFT for DTV pilot signal	Partial coherent detection using DTV pilot. Filter around pilot to reduce noise power. Use FFT as partial coherent detector for sinusoids	Signal contains narrowband pilot tone	Sensing time and robustness
Run-time noise calibrated detection	Noise is calibrated during run-time leading leading to robustness gains.	Asymmetric use of degrees of freedom	Robustness gains
Dual FPLL pilot sensing	Use two Digital PLLs which are preset to $\pm 30\text{kHz}$ around the pilot. Use time to converge as test statistic.	Signal is modeled as wide-sense cyclostationary	Simplicity of implementation
Eigenvalue based detection	Utilizes the fact that white noise is uncorrelated across samples/antennas while a bandlimited external signal is correlated.	Bandlimited primary signal and secondary radio has multiple receive antennas	Sensing time gains
Event-based detection	The detector tries to detect arrival/departure of signals. This technique can be used for identifying time- domain holes.	Primary user ON/OFF durations are much shorter than the time between secondary user movement	Robustness gains

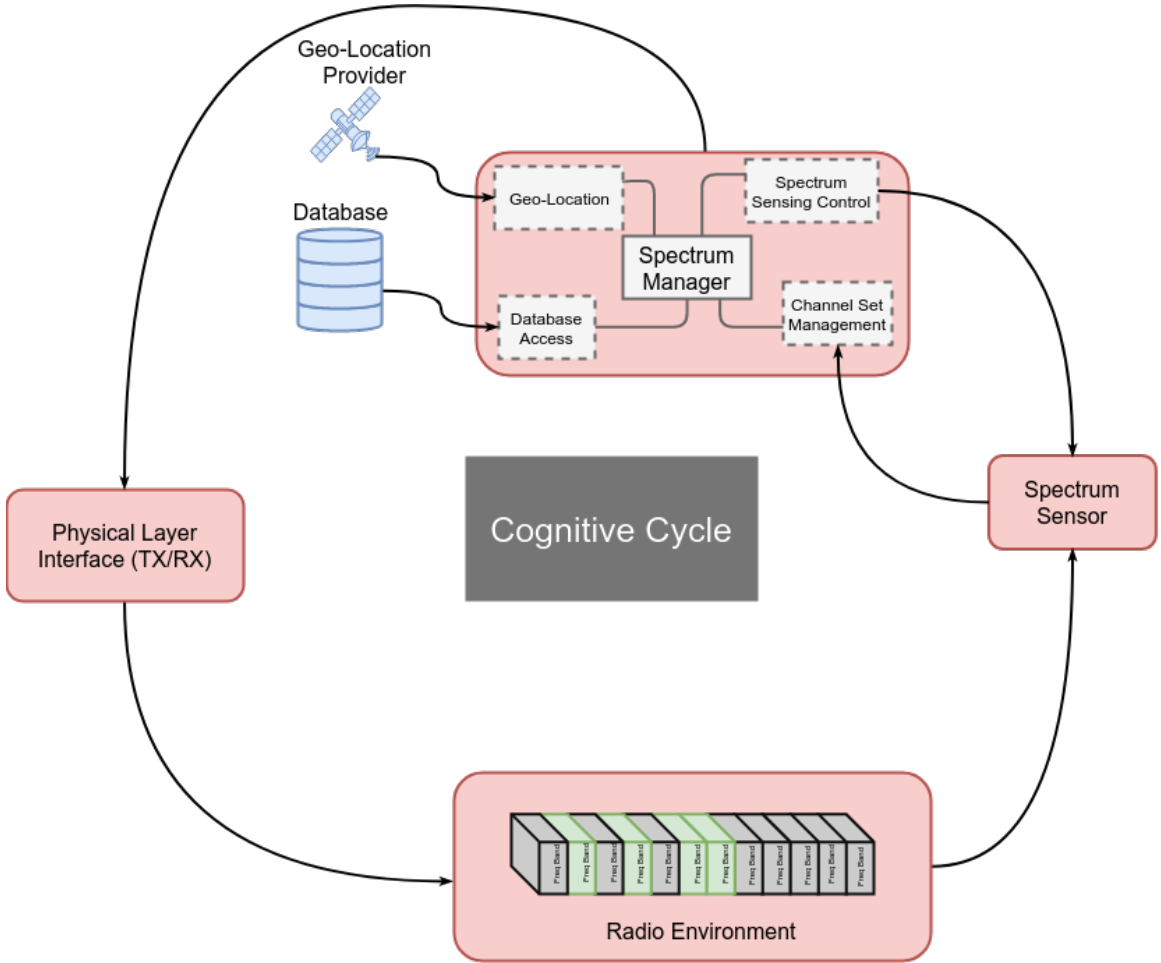


Figure 2.4: Cognitive Cycle

This motivated the research into alternative Spectrum Sensing approaches that minimize that effects as mentioned above. Cooperative sensing has shown potential in this domain as can be seen in[2]. Cooperation allows taking advantage of a spatial diversity and possible sensing information aggregation to boost sensing accuracy, with that said it could also result in additional overhead as a consequence of the additional management traffic, propagating throughout the network and occupying bandwidth, consuming extra energy and increasing latency.

In [2] extensive analysis for the state- of-the-art of cooperative sensing is provided, and it describes the issues characteristic of cooperative sensing, the gains, and the drawbacks.

Chapter 3

Cognitive Radio Networks Simulator

3.1 Motivation and Related Work

Simulations have proven to be of paramount importance in research of all kinds, and Wireless Communications is no exception. On the contrary, it has been growing in demand and importance with the increase in Networks Complexity and the exploding growth in computing devices and their data communications needs.

Wireless Networks Simulations, for that matter, even compete with Large-Scale testbeds, by providing platforms and tools that allow flexibility and controlling network environments and allowing scalability, rapid prototyping, and reproducibility. With other exploitation possibilities such as in Education where Simulation tools can be tailored and used to present Networking Concepts in a detailed, visually clear and tinker-friendly setup.

With that said, some of the fundamental goals of our effort to develop a Cognitive Radio Networks Simulator are:

- To allow flexibility and implementation Simulation scenarios with different topologies and Architectures, whether centralized or distributed.
- To enable scalability, simulations that could scale up to realistic network deployments that reflect real usage targets for the designed network.
- To allow as much realism as possible, realism in the context of Network Conditions that

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models real-world conditions, whether that is Propagation, Pathloss, Mobility, Transmission Patterns ...etc

Also realism in the context of various Network Protocols involved in the building of the Networking Stack (TCP/IP, HTTP, Routing Protocols ...etc). Where the behavior of such protocols comes with as much standard-compliance as possible, while provides a "hackable" environment that allows for possible modifications and optimizations that could arise as a consequence of using them in new Cognitive Network Architectures.

The landscape of current Wireless Network Simulation Environments is quite diverse when it comes to the available options, and favoring a particular platform over all the others is not necessarily an easy argument to defend [83]. With that said, numerous studies have been done to analyze and compare performance, scalability, flexibility of the various available simulation environments for Wireless Networks Researchers

Various attempts are made to satisfy the need for Simulation tools that is specifically tailored to the needs of Cognitive Radio/Heterogeneous Networks research community. For instance, a general idea of the main Simulators used by the research community can be extracted from [83, 47, 89, 48, 66] and displayed in Table 3.1

Another criterion that proved to be of big importance in this work, is the availability and the ease to modify and extend the simulation tool. This option is not a main feature of commercial tools which are financially expensive thus any solution developed within will be restricted to the researchers who opt to buy the same tool, which is not the purpose of our effort. Plus, commercial licenses put restrictions on the ability to access simulator's source code and later code distribution of developed models, which, again, conflicts with this work's goals.

In addition to that, browsing through the literature of available Simulation Tools tailored for Cognitive/Heterogeneous Networks shows that the primary available solutions represented can be summarized as in Table 3.2.

As can be seen from the Table 3.2, the major issues with available tools are very serious ones when it comes to efficient, reproducible and flexible studying of Cognitive/Heterogeneous Wireless Networks related research problems. CogWave[52] while being advanced in its physical layer capabilities, its design goals do not fit the needs we outlined in our research problem, it does

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Table 3.1: Features of Major Wireless Networks Simulators.

	NS-3[72]	NS-2[59]	OMNET++[79]	OPNET[63]	Qualnet[76]
Platform Target	Networks	Networks	Networks/ Systems	Networks/ Systems	Networks
Development	C++/Python	C++/OTcl	C++/NED	C/C++	Parsec
GUI Support	Average	Average	Good	Good	Good
Availability	Open Source	Open Source	Open Source	Commercial	Commercial
Protocol Stacks	Most Layers	Most Layers	Most Layers	Most Layers	Most Layers
Standard Compliance	High	Variable	Variable	High	High
Physical Layer Accuracy	Average	Low	Low	High	Average
Scalability	High	Low	Average	Average	High
Emulation	Yes	Limited	Limited	Limited	Yes
Extensibility	Excellent	Good	Excellent	Excellent	Excellent
Documentation	Excellent	Good	Good	Excellent	Good

Table 3.2: Comparaisn between available CRN Simulation tools

	Platform	Scope	Scalability	Extensibility	Protocols support	PU Models
CogWave[52]	Emulation/ Testbed	Physical Layer	Low	Excelent	Limited	Good
crSimulator[49]	Omnet++	Networks	Low	Limited	Limited	Limited
CogNS[29]	NS2	Networks	Low	Limited	Limited	Limited
Omnet++ ext[65]	Omnet++	Networks	Low	Limited	Limited	Limited
CRE-NS3[3]	NS3	Networks	Low	Limited	Limited	Limited
TFRC-CR[4]	NS2	Networks	Low	Limited	Limited	Limited
MIXIM ext[56]	Omnet++	Networks	Low	Limited	Limited	Limited
CRCN[25]	NS2	Networks	Low	Limited	Limited	Limited

not scale up and doesn't provide an environment for quick experimentation with various combinations of protocols in a cost-effective way. CogNS[29], CRCN[25] and TFRC-CR[4] are based on the old and obsolete NS-2 simulator, that is out of development for many years. Plus its segmented models and protocol implementations do not integrate seamlessly, thus reusing these cognitive simulation extensions with pre-existing models is problematic, one has to deal with the complexity of any desired protocol if one needs to use it in a cognitive simulation.

The same integration and protocol compatibility issues are raised in crSimulator[49] and the other omnet++ based simulators[65, 56]. The solution proposed in CRE-NS3[3] is closest to our attempt and is based on the NS-3 simulator, but it misses the point in using many advanced NS-3 functionalities and is limited in its capabilities of realistic PU behavior modeling that could be efficiently achieved with a better integration with other NS-3 models of various Wireless Technologies. Also its extendability and scalability are not satisfying for the needs of current research in Cognitive Radio Networks field.

With all that said, we opted to invest our effort in designing a novel modern simulation tool base on the NS-3 project[69] for reasons that will soon become clear. NS-3 enjoys a rich set

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of available feature; setting up a simulation is straightforward and relatively easy. NS-3 follows a conceptual structure that tries to be as close as possible to real world networking concepts. NS-3 applications mimic real world applications (basically any form of traffic generator), ns-3 NetDevices mimic network cards/interfaces of real devices, ns-3's network/internet stack coincides with real world networking/internet stacks available in operating systems, the same things goes for Physical layer and channel model.

Plus, NS-3 enjoys accurate packet level simulations and transport packets with real/standard-compliant bytes, allows for versatile statistics measurements and data collection and above all is memory and runtime efficient [83, 66, 47, 89]. In addition, the NS-3 simulator up-to this moment supports the following wireless technologies[70]:

- Wifi technology:
 - 802.11a, 802.11b, 802.11g physical layers
 - basic 802.11 dcf with infrastructure and adhoc modes
 - QoS-based EDCA and queueing extensions of 802.11e
 - various propagation loss models including Nakagami, Rayleigh, Friis, LogDistance, FixedRss, Random
 - two propagation delay models, a distance-based and random model
 - various rate control algorithms including Aarf, Arf, Cara,
 - Onoe, Rraa, ConstantRate, and Minstrel 802.11s (mesh)
- Wimax technology:
 - Uses available propagation and loss models from the wifi module.
 - a scalable and realistic physical layer and channel model
 - a packet classifier for the IP convergence sublayer
 - efficient uplink and downlink schedulers
 - support for Multicast and Broadcast Service (MBS)
- LTE Module

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- Dynamic Spectrum Access
- Inter-cell Interference Coordination
- QoS-aware Packet Scheduling
- Radio Resource Management

- 802.11p wireless based vehicular communication
 - Focus on Mac/Phy layer compatibility at 5.9Ghz

- 6LoWPAN: Ipv6 over 802.15.4
 - Compliance with RFC 4944 and 6282

- Spectrum Module

A major point that strongly motivated our choice of NS-3, is its frequency-dependent simulation capabilities. The Spectrum Module[13] provide an API and a set of classes to model rf signals and a channel implementation that models technology-independent signals base on based on a power spectral density signal representation. A signal is thus, an object characterized mainly by its duration and its Power Spectral Density (PSD). The PSD is defined as a vector of discrete scalar values corresponding to frequency subbands. The resolution of the PSD representation, thus the number of subbands is configurable, to allow a context-specific compromise between high-computational load needed with high resolution but realistic PSD representation and less realistic but more computational efficient representation.

This modeling choice also leaves a great flexibility to the other model developers in writing simulations that incorporate different spectrum models representing different wireless technologies in the same scenario, interacting together with a straightforward ability to see interference and signal propagation effects.

In this Chapter, we present in section 3.2 initial attempts to simulate Cognitive Radio Networks in the context of studying the interaction between adaptive radio systems and adaptive services a work that helped motivate the effort to develop a more capable Simulator. Later on, we describe in section 3.3 the Simulation framework and the architecture adopted for the simulator. In section 3.4 we move on the describe the simulator components that enable its various features

and provide implementation details. We also present some evaluation results that demonstrate our Simulator in action, applied to some typical Networking Scenarios.

3.2 Cognitive Multimedia Radio Networks Simulations

At an initial step towards the Cognitive Radio Networks simulation framework we are proposing, we considered implementing a simple Cognitive Radio simulator that instead of performing Spectrum Sensing operations, it generates random local operations that simulate sensing, channel availability ...etc. The modeling of the radio part of the environment is based on the scheme proposed in [80]. Heterogeneous PUs are envisaged, each characterized by its own bandwidth, activity and sensitivity levels. Cognitive users sense the radio environment, identify the different PUs and create a list of transmission opportunities by defining the available throughput for each one of them.

Identification of the type of PU, and not only presence of transmission, is relevant as it allows a more accurate characterization of transmission opportunities based on know channel structure. Localization has been recently added [81] to this algorithm as it allows understanding the spatial distribution of PUs and therefore improves estimation of interference. This simple simulator was used to test the possibility of achieving full adaptive communications, employing a joint cognitive networks (CR) and scalable video (SV) with multiple descriptions (MD) as an additional source of flexibility and robustness. The result of this is that each cognitive device may introduce additional metrics into a routing algorithm that weights available bandwidths, route independence, and mobility to create an end to end path for the video stream to be delivered.

3.2.1 Scenario Description

The target scenario is a multihop delivery system transferring a video coded using the H.264 standard. The video is encoded in two substreams (the descriptions) transmitted along two different radio paths. The radio environment is considered to be heterogeneous with different primary users independently active in the same area. The radio paths may, therefore, be chosen among any of the available combinations of radio channels and geographical paths, thus transmitting the

descriptions exploiting either the spectrum band of different primary users (PUs) and different geographical routes. We foresee two different options for each intermediate forwarding node:

1. The node receives only one description. In this case, selection of next hop is rather straightforward based on the list of available channels.
2. The node is receiving both descriptions. In this situation, the node needs to evaluate the forwarding strategy (channel, path) for both descriptions maximizing their independence.

One of the characteristics of CR systems is that they may opportunistically exploit PU bandwidth provided they vacate the channel when activity from the PU is resumed. This may force sudden changes in available bandwidth. Therefore, we add scalability on top of each description to allow fast local adaptation.

3.2.2 Video source

The scalable multiple description coding approach adopted in this work is the one presented in [30]. The developed method introduces simple pre- and post-processing schemes to generate substreams that can be coded using a standard H.264/SVC coder. In the pre-processing part, the original sequence is down sampled by rows and columns generating four sub-sequences that can be independently coded as in polyphase spatial subsampling-MD method. To reduce redundancy two of the subsequences are predicted from the others by using the tools that guarantee scalability in the H.264/SVC coder. This approach, called Inter Layer Prediction Spatial Multiple Description Scalable Coding (ILPS-MDSC), takes advantage of the inter layer prediction method of H.264 that allows reduction of redundancies among quality layers by adopting either spatial or motion based prediction strategies depending on which provides best results. Each group of four adjacent pixels then leads to two descriptions, in which one of the subsequences is derived from subsampling, acts the base layer and another is predicted and represents the enhancement layer. When bandwidth constraints forbid the transmission of a whole description, the enhancement layer is dropped. Since the two descriptions follow independent paths, different combinations of received information are possible, from just one to all four original subsequences. Since the subsequences are obtained via subsampling, recovery of the missing information is performed by interpolation. Coding rate as-

signed to each subsequence may be tuned to obtain a whole set of rates and ratios: this allows additional degrees of flexibility although not all combinations are equivalent in quality terms [30].

The scheme has been proven to be effective over IP networks even in case of packet losses and peer-to-peer networks with two levels of adaptation: one provided by the above scheme, the other providing feedback to the encoder to adapt coding parameters of bandwidth changes are effective for longer periods. In this work, we apply the scheme to a cognitive system, whose available bandwidth is highly variable depending on the activity of PUs.

3.2.3 Simulation results

Simulations have been so far conducted for a single cognitive node, i.e. representing a two-hops path. The node receives both descriptions, matches the available re-transmission bandwidths with those of the scalable descriptions and decides if each description may be forwarded as a whole if only the base layer or even if nothing can be transmitted. A number of PUs is randomly generated as well as the channel conditions. Sensing is performed every second and a report is sent to the video encoder every 10 seconds.

Several simulations have been run for this environment. The following figures represent some of the available results. Figure 3.1 represents a snapshot of time variations in received quality due to bandwidth variations. Note that no delay is introduced, i.e, no buffering is performed in the cognitive node to smooth video peaks. So real-time transmission is considered. Figure 3.2 represents the average and dispersion intervals of quality received when any of the possible combinations of subsequences is received (only one base layer, full description,).

So far, simple routing strategies have been tested without exploitation of the cognitive part. This is currently being deployed and will allow several metrics to be tested besides the received quality, such as the effect of localization information, detection errors, the presence of other users, and energy consumption.

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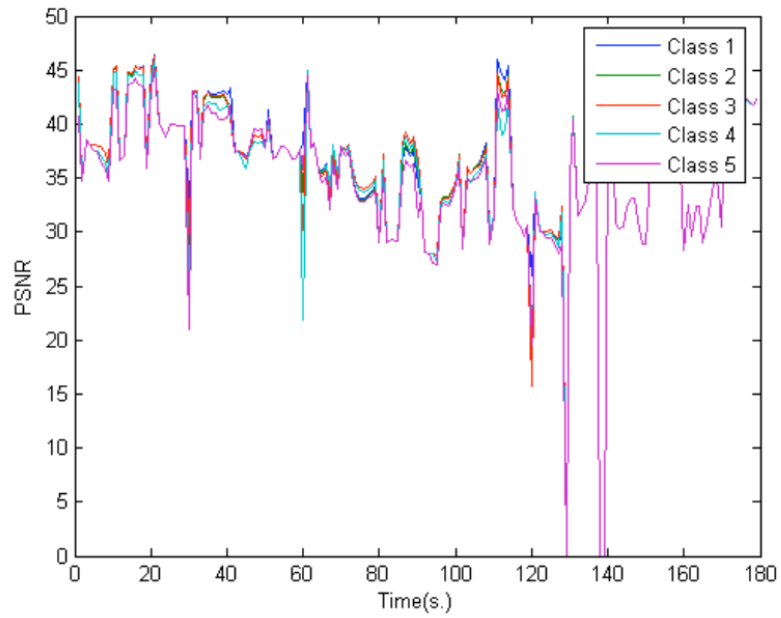


Figure 3.1: Time Variations in PSR

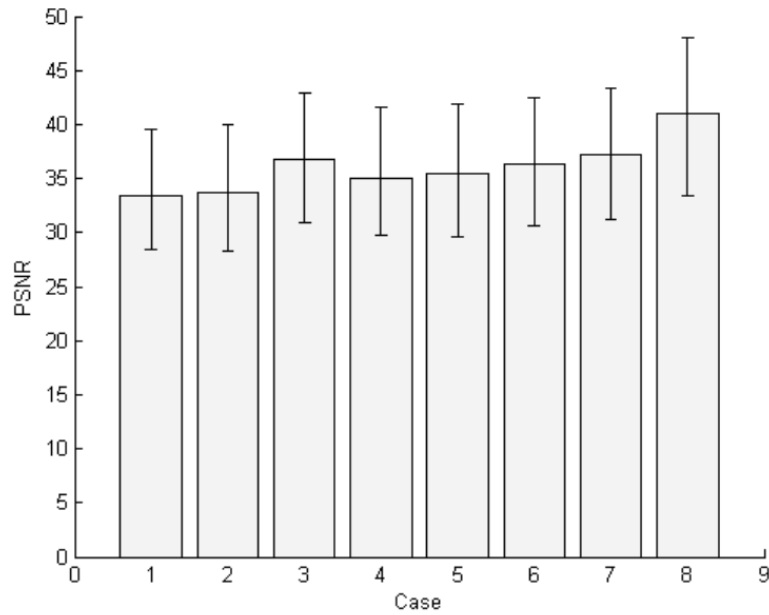


Figure 3.2: Aggregate PSNR depending on received subsequences

3.3 CRN Simulation Framework

The simple simulator described in section 3.2, offers very limited options for general purpose cognitive radio simulations, its level of simplification of cognitive radio behavior (no real spectrum sensing, no frame structure ...etc) offers very little opportunity for performing advanced and more general cognitive radio networks simulations. Moving on from that, we describe, in this section, a much more advanced simulation framework, in terms of modeling capabilities and potential applications.

Figure 3.5 depicts the overall architecture and the main components involved in the design of this Cognitive Radio Simulator. Through following good implementation practices as suggested by the NS-3 Project when it comes to integrating new models, our design reuses as much as possible from pre-existing models.

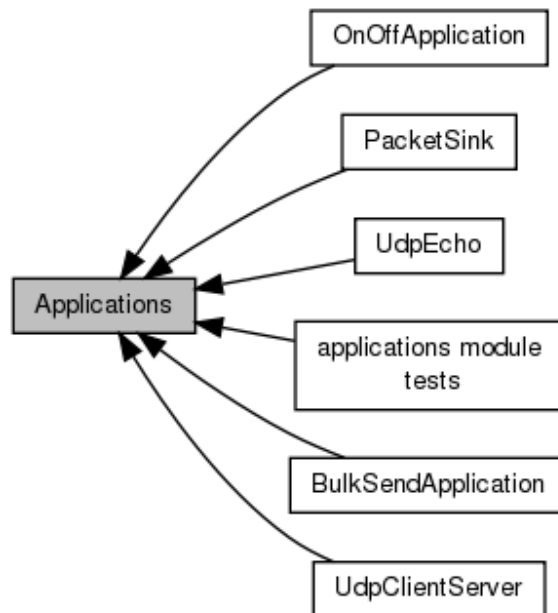


Figure 3.3: NS-3 available Application Layer models

For instance, since the application and mobility models are decoupled from other models, basically any application layer model within NS-3 can be used on top of our simulation framework. (possible applications and traffic generators are shown in Figure 3.3), the same thing goes for the Mobility model (possible mobility models are shown in Figure 3.4). Going down to the Internet and

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network layer, various protocols stacks can be plugged in ranging from routing protocols (static, AODV, DSR ...etc) and TCP flavors (Reno, Hybla, Westwood, Vegas ...etc) independently from the other parts of the simulation. The components in red in Figure 3.5 are where the actual work on our simulation framework is added to NS-3 and are organizing in a set of classes that follow, as much as possible, the NS-3 architecture for easy integration with its design flow, as we explained earlier.

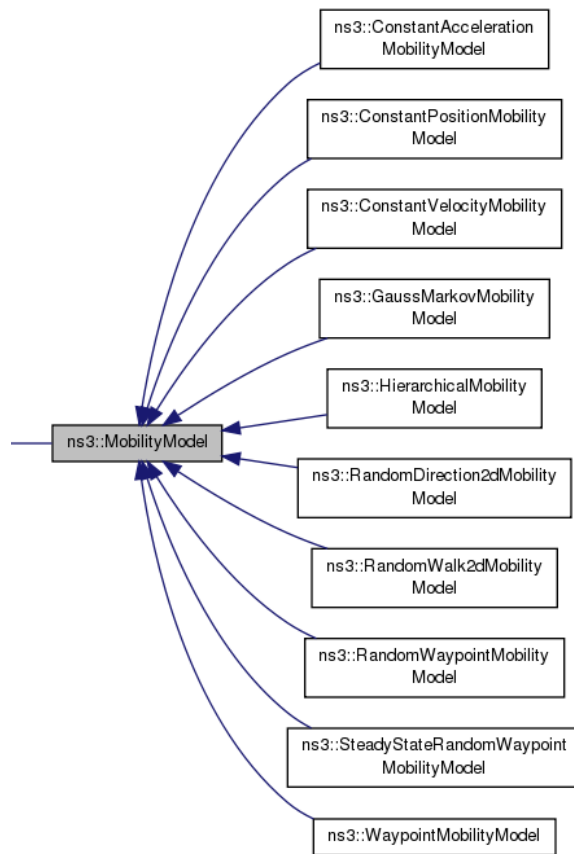


Figure 3.4: NS-3 available mobility models

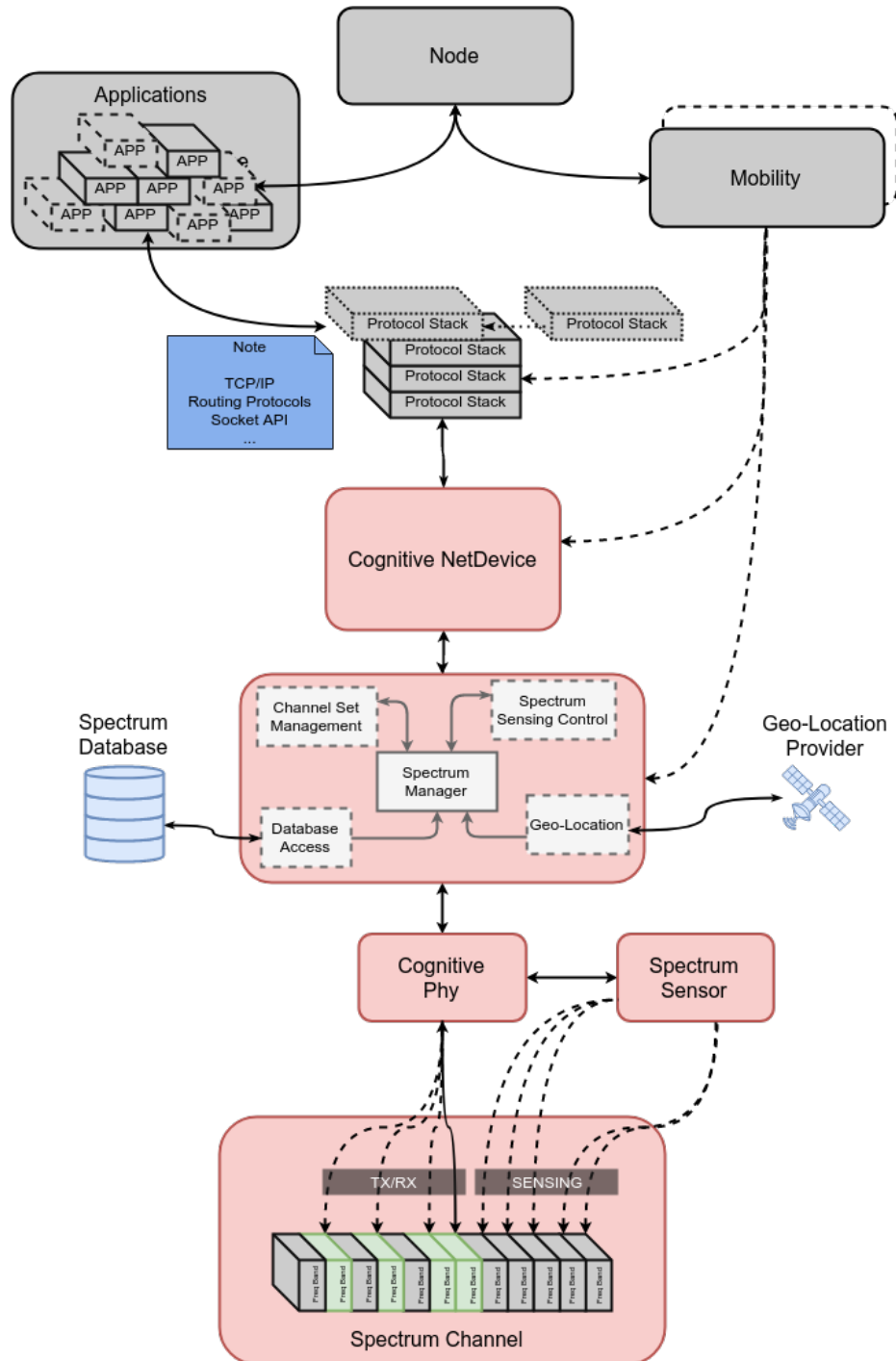


Figure 3.5: Cognitive Radio Network Simulator Architecture

3.4 CRN Simulation Models

3.4.1 Cognitive Node Model

A cognitive node in our framework is no different than a regular ns-3 node, it subject to the same work flow regarding declaration, interaction with other models and operation. Depicted in Figure 3.6 is the high-level architecture[68].

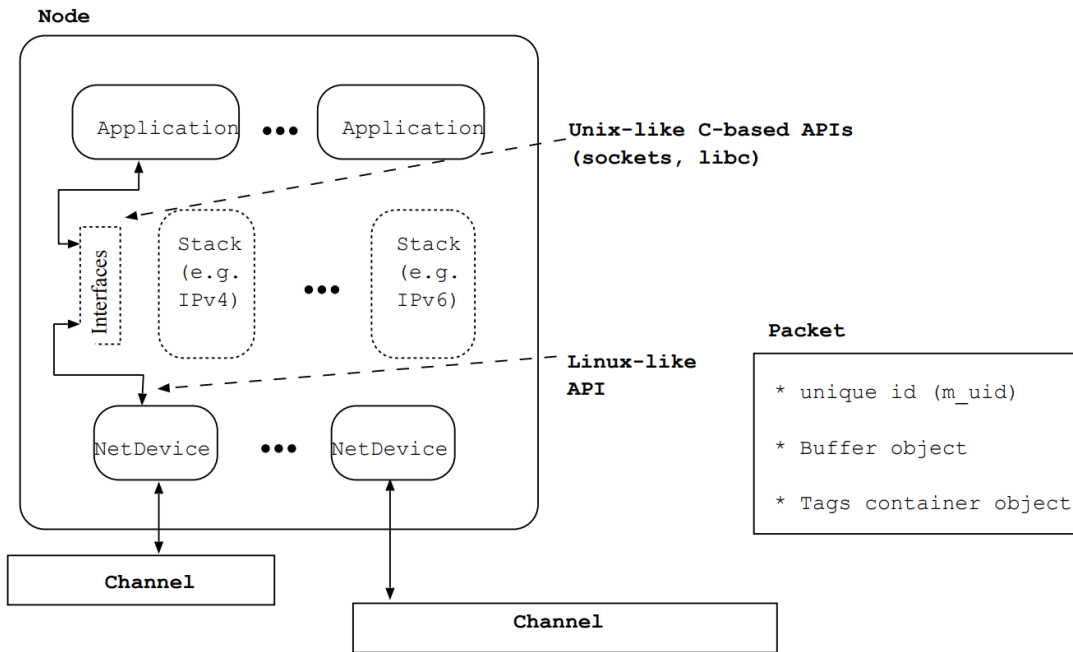


Figure 3.6: High-level node architecture[68]

The Node class in ns-3 abstracts the notion of a

3.4.2 Cognitive NetDevice Model

In NS-3 terms a NetDevice is a Network layer to device interface, it is intended to contain the implementation of MAC layer features and APIs to provide APIs for upper layers to manage a network device. Figure 3.7 shows a sample list of technologies implemented through the NetDevice class.

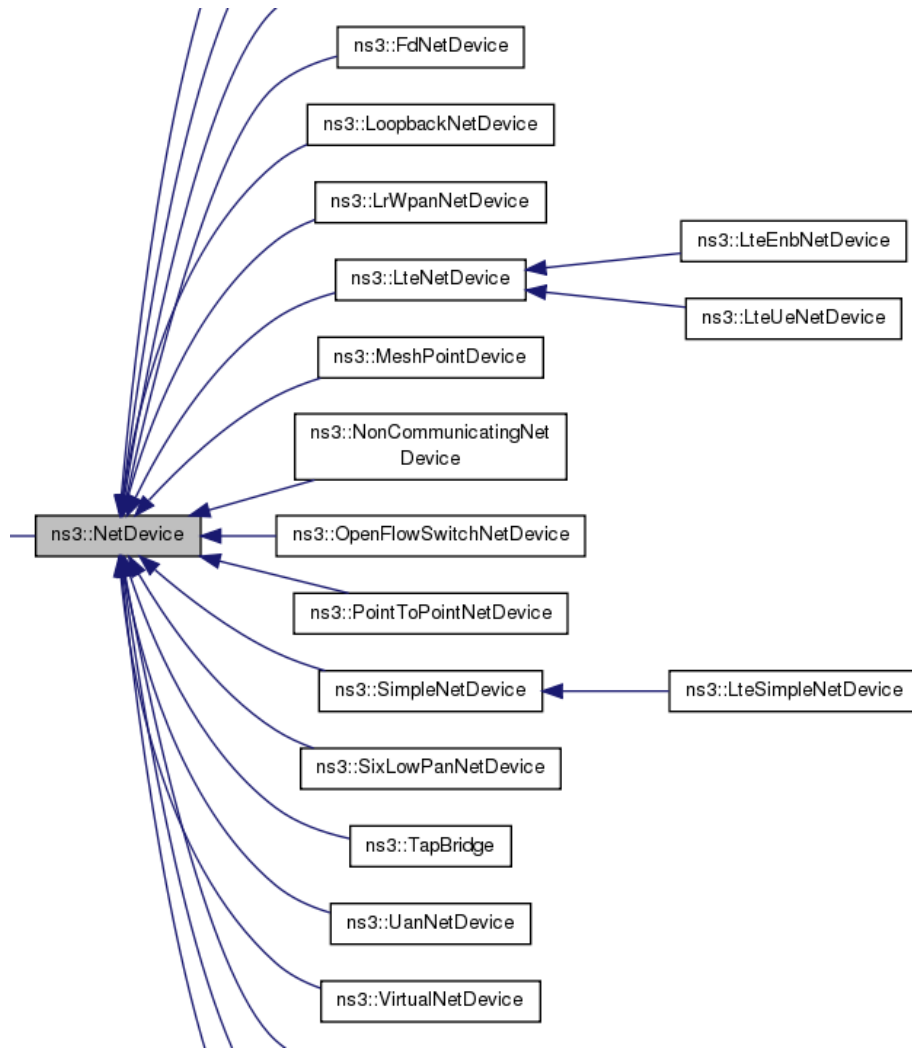


Figure 3.7: NS-3 implemented NetDevices[69]

This class was designed to hide as many MAC-level details as possible from the perspective of layer 3, in order to allow a single layer 3 to work with any kind of MAC layer. Specifically, this class encapsulates the specific format of MAC addresses used by a device such that the layer 3 does not need any modification to handle new address formats. With that said, any implementation of MAC layer behavior in the context of Cognitive Radio, would ideally be implemented at this level as this class hides any MAC specific details from upper layer and provides a decoupled container for MAC layer experimentation. Thus we opted to sub-class the NetDevice into a CognitiveNetDevice and implement the necessary methods as defined by the parent class. This class will eventually interact with the other CR simulator components, mainly the Spectrum Manager to coordinate on

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Spectrum Sensing and Spectrum Access. This CognitiveNetDevice's MAC implements a frame-by-frame behavior. Transmission time is divided into Frames of duration T within which the CR node can perform spectrum sensing for a duration (Figure 3.8) if any primary users are detected the CR node waits till next frame to perform sensing again on the next supported channel otherwise it starts transmission.

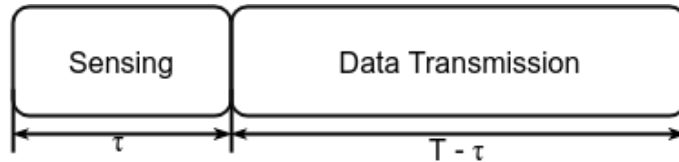


Figure 3.8: Frame Structure

Figure 3.9 depicts the logic behind the CognitiveNetDevice transmission behavior. When the NetDevice is first started initiates a first MAC frame, thus it immediately starts Spectrum Sensing on a pre-configured initial channel. No transmission shall begin unless spectrum sensing yields a clear channel available for secondary utilization while sensing possible received packets from upper layers are queued and eventually dropped if too much waiting time is incurred and the queue is full or if all channels are sensed and no clear channel is identified. When a free/clear channel is identified, transmission starts immediately by reading queued packets or transmitting packets received from upper layers in this order. Transmission lasts for the rest of the Frame as depicted in Figure 3.8.

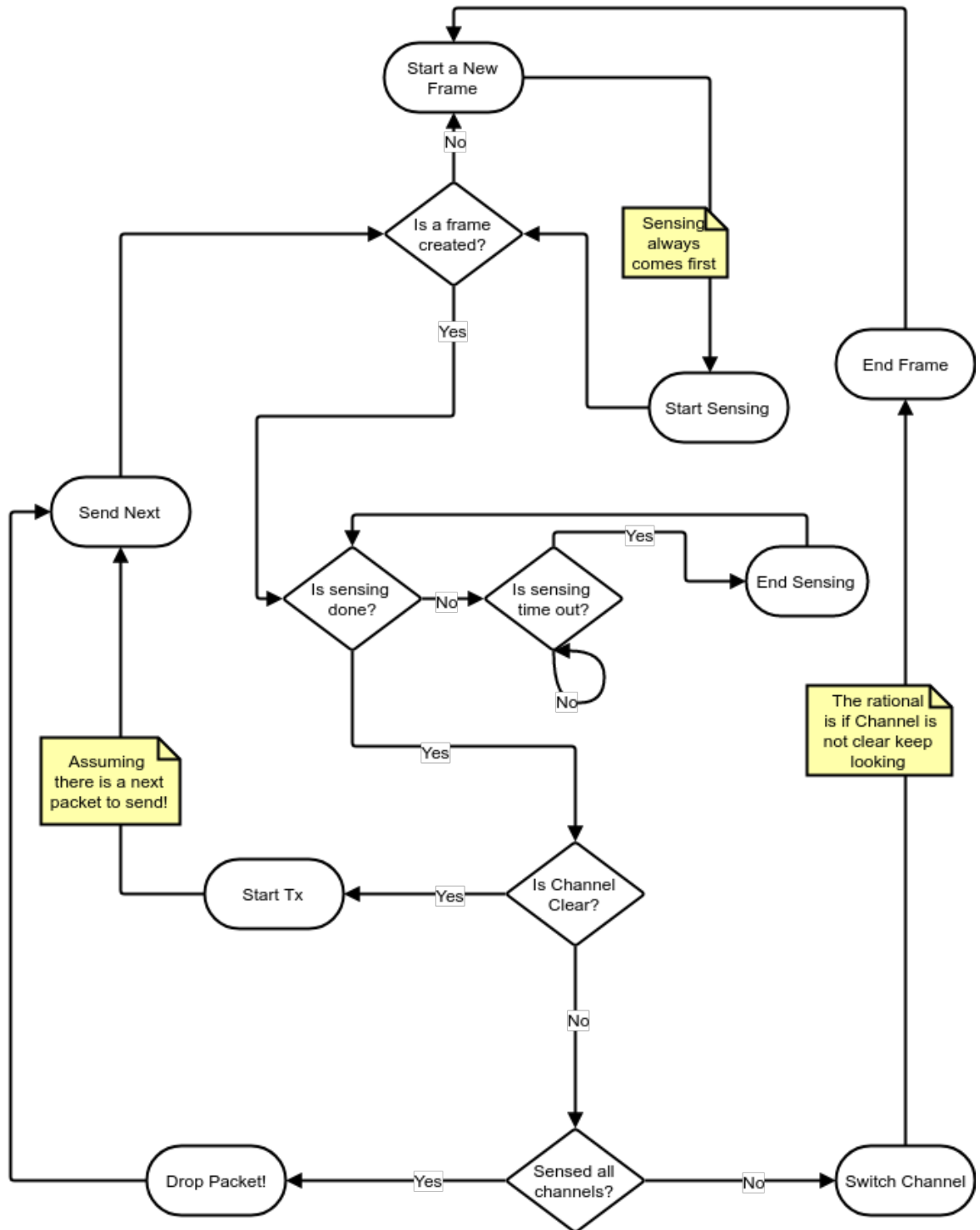


Figure 3.9: Cognitive Transmission Policy

3.4.3 Spectrum Manager Model

The Spectrum Manager (SM) is the structure where high level cognitive abilities are implemented, information aggregation, channel selection, decision making ...etc. Thus it acts in a way like the brain of the Cognitive Radio, it implements the cognitive cycle as depicted in Figure 3.10.

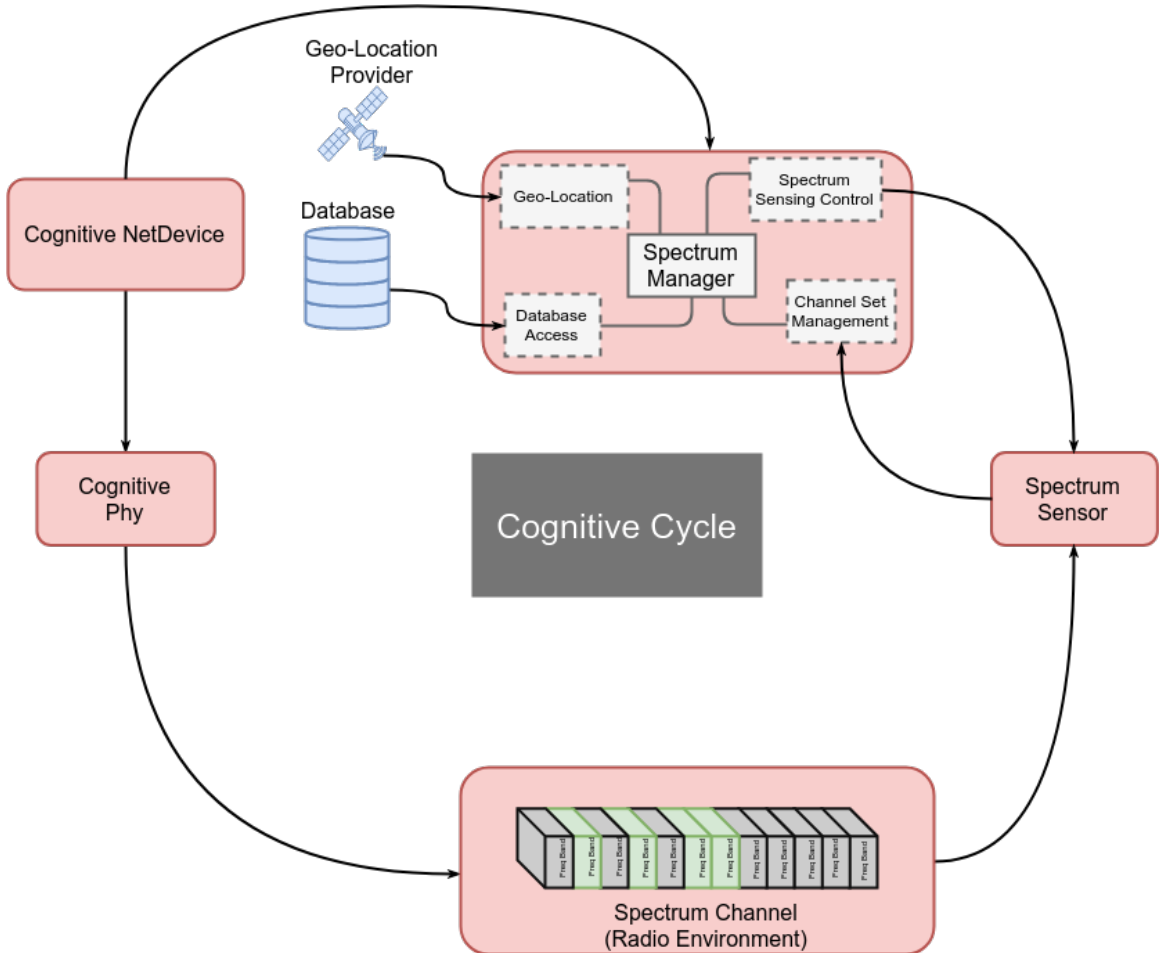


Figure 3.10: Cognitive Radio Networks Simulator: Cognitive Cycle

As an entity, it is supposed to be located in nodes where such cognitive abilities are important, in the case of a centralized cognitive radio network it might be sufficient and more optimal to restrict the deployment of a Spectrum Manager (Cognitive Engine) to the Base Station of the network. In a distributed network without a central entity, decision making is made locally based on aggregated and distributed information circulating throughout the network thus the cognitive ability is necessary on every node of the distributed network.

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Channel selection policies, data aggregation, and decision making are all functionalities that are supposed to be implemented at this level, within this class.

The current implementation inspires from the workflow defined in IEEE 802.22 standard specification of the Spectrum Manager[11]. For instance, the channel set categories and transition behavior is as depicted in Figure 3.11 where their description is following. The sets not relevant in our design are mentioned as such:

- Event 1: When an incumbent is detected the operating/backup/candidate channels move to protected set.
- Event 2: No incumbent around.
- Event 3: Not relevant
- Event 4: Channel no more needed, devices goes offline.
- Event 5: The channel is selected to become operational
- Event 6: Not relevant
- Event 7: Once a channel is sensed as free for sure, it becomes candidate.
- Event 8: The channel is occupied or not sensed recently as clear.

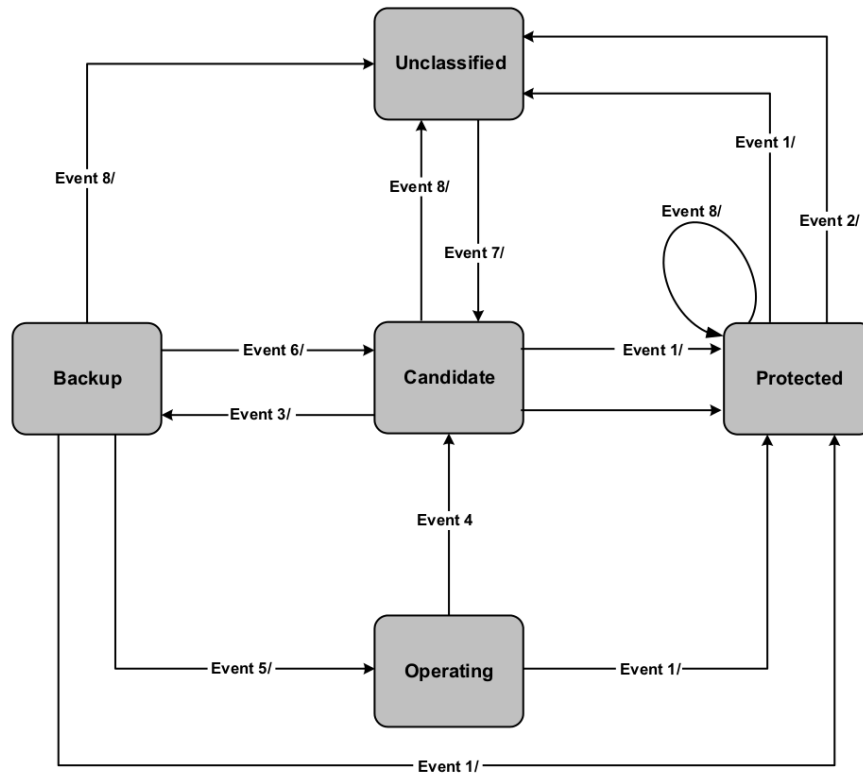


Figure 3.11: Channel set transition diagram

3.4.4 Cognitive Physical Layer Model

This model inherits directly from the SpectrumPhy to implements the basic Physical Layer functionalities according to the NS-3 architecture, like transmission and reception of data frames to/from the associated SpectrumChannel. It also interfaces with the Spectrum Manager and behaves according to the operation policies decided by its cognitive process, thus it also implements the actual spectrum sensing capabilities through the Spectrum Sensor model that will be described afterward.

The different parameters such as sensing duration and switching duration can be directly controlled by upper layers. Sensing results and different Signal related statistics are also reported to Upper Layers, mainly to the Spectrum Manager for eventual processing and decision making.

The CognitivePhy model is the gateway to transmission and reception operation, to and from the spectrum, it implements the switching operation between different states and provides the hookups that allow for the integration of the Energy Model for runtime measurements of energy

consumption due to RF operations.

3.4.5 Spectrum Sensor Model

This model encapsulates the specific techniques implemented to model a spectrum sensing operation on the communication medium. It interfaces directly with the Cognitive Physical Layer to serve the Spectrum Manager and executes the sensing policies decided after analyzing acquired information about the network environment.

The Spectrum Manager's operations can definitely be aided by an access to a Spectrum Database that might reduce the need to perform spectrum sensing, especially in a centralized setup. But even in a centralized setup direct spectrum sensing might be needed in the cases of PU incumbent activity while using a database-acquired spectrum information, and the need to quickly shift to a new channel of operations when no backup channels are available. In the case of a distributed network, the need for a spectrum sensing ability becomes even more obvious. Thus the spectrum sensing ability is paramount to all types of nodes operating in the network, whether distributed or centralized.

The spectrum sensing works for a set window of time, provided a specific channel number (channel), sensing mode (currently only energy detection). It also is capable of performing wide-band sensing with ease, which allows the construction of more advanced Cognitive Radio Simulations, a feature which was lacking in all the reviewed simulation frameworks. The spectrum sensor is developed to be modular, thus its functionality can be exploited in other NS-3 models, basically to enhance an existing NetDevice implementation with a spectrum sensing capability. This could be very useful to experiment with heterogeneous coexistence mechanisms that rely on spectrum sensing and the detection of traffic patterns of the competing wireless network.

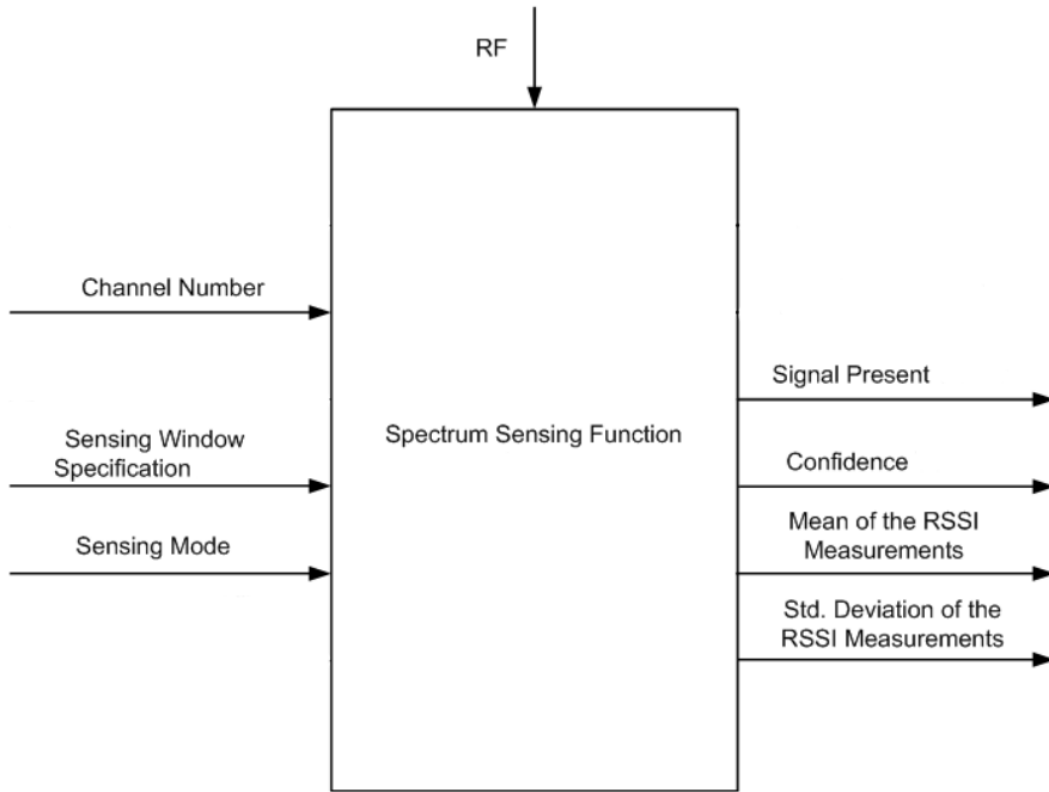


Figure 3.12: Spectrum Sensing Function[11]

3.4.6 Spectrum Database Model

A Spectrum Database is implemented as service that is accessible by the Spectrum Manager whenever a new Spectrum Information is needed for a specific node at a specific location. The Spectrum Manager calls the Spectrum Database Service (SDS) to update a list of Spectrum Holes while providing the location for which it wants the new updated list. After which the SDS access it is a pre-configured database of Location-tagged Spectrum Holes to fulfill the SM's request.

In this design the SDS allows implementation of different ways to implement an actual database, it can either access a database loaded at runtime by parsing a user-supplied configuration of Spectrum Holes and locations in a text file (the default implementation). Or it can even interface with Publically available Spectrum Database services such as Google's[34] or Microsoft's White Spaces Database[60]. In the case of Google's database, for example, access can be granted through a JASON-RPC[35] based network API. A licensed holder (a free limited license is available) send a

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request specifying its location of interest, Antenna configuration, and frequency-tuning capabilities and receives a list of Spectrum Holes that can be accessed at the time of request for a defined duration. Such a database implementation could be very helpful in designing realistic networking configuration the model behavior in real-world locations.

The following is a code snippet of how a Database Service could implement a database access, it basically creates a fixed set of Spectrum Holes on the fly and fills the provided channel-`sList`.

```
void DatabaseService::UpdateChannelList (GeoLocation *location ,
    std::list<SpectrumHole*> &channelsList)
{
    channelsList.clear();

    //Fill in the available channels list
    for (uint32_t i = 0; i < 5; i++)
    {
        SpectrumHole *sh = new SpectrumHole;
        sh->SetBandwidth(6e6);
        sh->SetCentralFreq(i + 7);
        sh->SetChannelNo(i);
        sh->SetLocationValidity(NULL);
        sh->SetMaxEirp(0);
        sh->SetTimeValidity(Seconds (0));

        channelsList.push_back(sh);
    }
}
```

3.4.7 Geolocation Model

As it is clear from the above descriptions, the Geographic location is very important when using a spectrum database model for spectrum management, thus a modeling of this functionality is necessary to complete the Picture.

Fortunately, in NS-3 access to a specific node's location can be very easily achieved as long as a pointer to that node's object is available in a straightforward way:

```
Ptr<Node> node ;  
...  
Ptr<MobilityModel> mobility = n->GetObject<MobilityModel> () ;  
Vector position = m->GetPosition () ;
```

3.4.8 Energy Model

The energy consumption and energy source models for different physical layer operations (TX, RX, SCANNING, SWITCHING, IDLE, SENSING) are modeled using NS-3's energy framework[85]. The power supply allows the devices to draw power from an energy source; it also allows depletion notification upon consumption of total defined power. It also allows tracking of power consumption throughout the device's runtime. This enables the the Cognitive NetDevice to track its energy consumption and for the Spectrum Manager to eventually consider such information for more optimal energy-aware decision making.

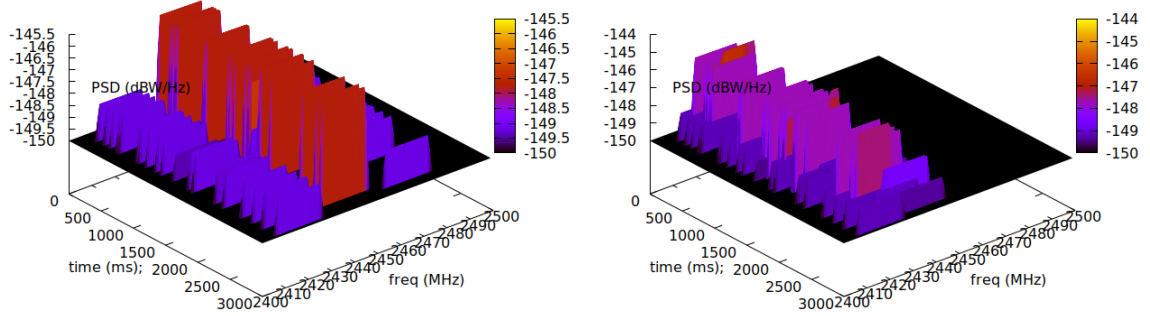
3.5 Simulator Evaluation

We attempted to validate the components of the simulation framework through a series of simulations. In order to validate the functionality of the wide-band spectrum sensor, we constructed a topology with a varying number of Primary Users accessing a variable set of pre-defined spectrum bands then, we launched the spectrum sensor in wide-band sensing mode to collect information on channel availability.

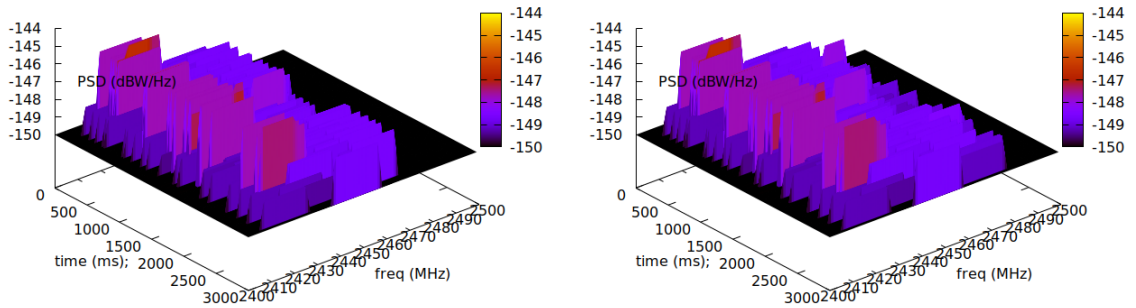
The plots in Figure 3.13 are generated from an environment with 11 possible bands in the 2.4GHz band. The bands correspond to the WiFi channels with 20Mhz bandwidth each. The

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various channels will be filled with PU traffic pattern, generated from PU users deployed on each channel and distributed in a rectangular area of 20mx20m dimensions and their positions are allocated following a uniform random distribution with min=0m and max=20m. The traffic pattern follows an exponential random distribution for the ON and OFF periods, with parameters 0.01 and 0.1 respectively[45] with a transmit power of 20dBm. The spectrum sensing node is deployed at location x=10,y=10 of the area, it performs spectrum sensing following a 1ms sensing resolution over a period of 3 seconds (which is the period of the simulation). Figure 3.13 show the ability of the spectrum sensor to detect incumbent activity on a wideband spectrum.



(a) Figure on left with 3 PU active channels, on the right with 5 PU active channels



(b) Figure on left with 9 PU active channels, on the right with 11 PU active channels

Figure 3.13: Spectrum Sensing Results in 2.4GHz band

Another simulation setup we created was a topology, where a Cognitive Node attempts

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to transmit UDP packets to an AP. The node and the AP are assumed to have a Common Control Channel (CCC) through which they exchange channel switching information, a mechanism that we ignore the technical details associated with it, like the latency associated with the exchange of management information, channel switching delay ...etc. We focused purely on measuring throughput performance of the Cognitive Node. The Cognitive Node performs spectrum sensing for periods ranging from 1ms to 10ms with a sensing cycle of 10ms, for a total simulation time of 3s. Whenever a channel is sensed busy it directly switch to a different channel along with the AP and attempt communication there. The PU traffic on the channels is as before, exponential ON and OFF periods with parameters 0.01 and 0.1 respectively and 20dbm transmission power.

Figure 3.14 shows the drop in Node's throughput with the increase of sensing time, a result in accordance with our expectations. Figure 3.15 shows a different plot, for the same simulation but instead of varying the sensing time, we fix it at 1ms and vary the sensing cycle in the range from 10ms to 60ms, this time it shows how the node's throughput increase when sensing periods are dispersed from each other but that also increase probabilities of interference with the Primary Users, thus we see fluctuations and sudden drops in the throughput as it follows a general increasing trend.

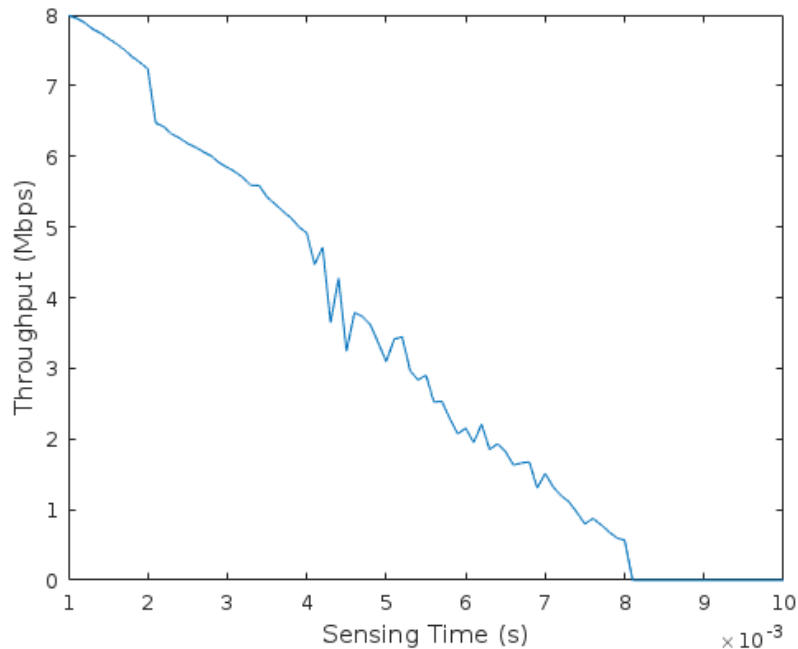


Figure 3.14: Spectrum Sensing Function[11]

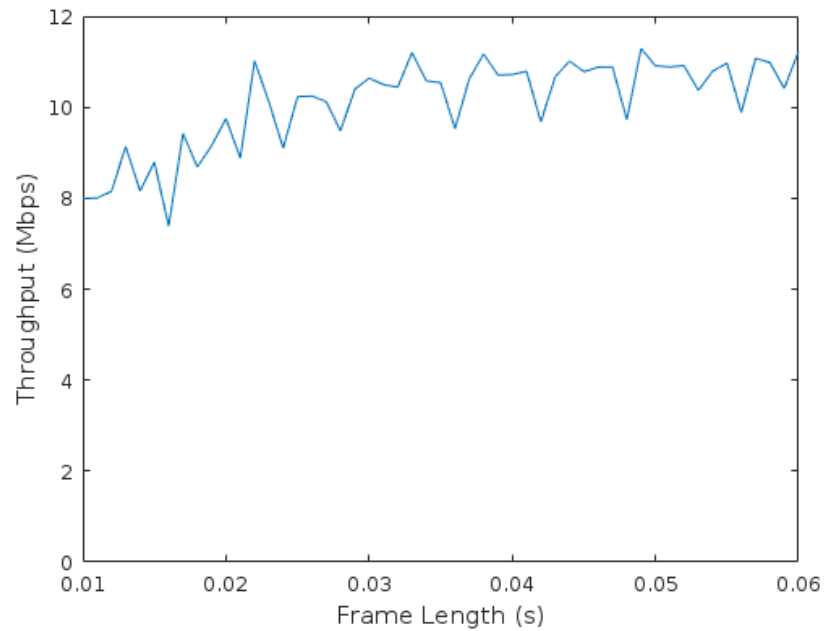


Figure 3.15: Throughput vs Frame Time

3.6 Conclusion

In light of current state of technological advancements happening on many different levels in Wireless Communications Networks, Dynamic Spectrum Access and Cognitive Radio concepts/techniques are here to stay and are seeing a proliferation all over the spectrum of networking architectures and standards. Especially given the ongoing trend towards 5G to move towards more integrated coexistence architectures, where networks adapt their service delivery approach based on scale and user needs within a single architecture, also the coexistence of heterogeneous networks to share the limited resource that spectrum is. The Cognitive Radio Networks simulation framework we developed in this chapter, is an environment of experimentation and validation to aid researchers in building advanced simulations that could reflect the complexity of real-world topologies while maintaining a fair amount of flexibility and versatility.

The ongoing evolution of this simulation framework is to put it into action through the modeling of an 802.22 like MAC protocol that integrates in-band and out-band sensing with coordinated distributed spectrum sensing and database access. Also, this framework will be the basis of our plans to experiment with more advanced Cognitive Radio techniques that prove difficult to

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experiment with physical testbeds, such as simultaneous sensing and transmission, a concept that can potentially increase significantly the capacity of CRNs. The development of error models and better Physical Layer models is also an important next step, plus the modeling of spectrum sensing inaccuracies due, not necessarily, to PU activity but to other sources of noise that could affect the sensing performance.

Chapter 4

LTE/WiFi Coexistence

In this Chapter, I present my PhD work done concerning tackling LTE/WiFi Coexistence as a practical Heterogeneous Networks Coexistence Problem. The work is divided into 3 parts:

- Implementing a Simulation/Emulation framework that merges between Packet Level simulation accuracy provided by NS-3 standard-compliant implementation of LTE MAC, and upper layers and MATLAB's standards-compliant and verified implementation of LTE's physical layer. In order to provide a framework for realistic studies of LTE, for example in the context of LTE/WiFi Coexistence.
- LTE/WiFi experimentation is of paramount importance, and we handled that by building a setup using open source solutions off-the-shelf equipment and USRP/Zedboard SDR platforms to allow the testing in real settings and the validation of some of our research.
- E-Fi is the result of a collaboration between our lab at Pavia University and the GENYSIS Lab at Northeastern University led by Prof Kaushik Chowdhury. We proposed a solution for the LTE/WiFi coexistence problem that does not assume LTE cooperation and focuses on WiFi's ability to adapt to a high interference environment. The proposal is then validation by simulations and experimental results.

4.1 Motivation and Related Work

Cellular traffic has increased 4000 times over the last ten years, propelled by the growing adoption of smartphones nearing 50% of the electronic device market [44]. Furthermore, emerging areas like the Internet of Things predict billions of connected sensors worldwide within next few years, which will further stress existing communication infrastructures. One solution to this problem is the proposed LTE Unlicensed (LTE-U) paradigm that uses the 5 GHz band for both enterprise-driven LTE and Wi-Fi networks by assimilating spectrum from the ISM bands. However, the strict time-bound frame transmissions within LTE and its extensive error recovery mechanisms raise concerns on the starvation of Wi-Fi in such shared spectrum use. This paper attempts to address this issue by first demonstrating the limitations of existing standards-specified coexistence techniques and then devising a new approach called Evasive WiFi (E-Fi) that combines Wi-Fi Direct and classical 802.11 distributed coordination function (DCF). When LTE and Wi-Fi coexist in the same spectrum, LTE is barely impacted, whereas the performance of Wi-Fi drastically degrades to 70-100% packet error rate [21]. LTE Release 10 includes eICIC (enhanced Inter-Cell Interference Coordination) that defines Almost Blank Subframes (ABS), which carry neither control nor data information. Primarily aimed for interference management between adjacent LTE small cells, the reuse of this technique for LTE and Wi-Fi coexistence was introduced in [7]. ABS allows Wi-Fi to gain access to the channel for a short time-frequency window, and by leveraging multiple ABS frames devoid of cellular traffic this window can be extended. There is a fundamental assumption in the research involving ABS scheduling so far: that Wi-Fi has truly uninterrupted channel access during the entirety of the ABS.

With the fast growth of cellular data usage demand nowadays [], better solutions for efficient and reliable data transmission are required. Given that one of the main restriction is the scarcity of spectrum, researchers are seeking paths to take advantage of all possible frequency bands, and the focus has been recently directed towards the unlicensed Wi-Fi spectrum; especially the 5GHz band. This band shows a luring growth potential with its relatively less traffic and an abundant amount of spectrum that could provide a viable coexistence environment for both LTE and WiFi communications. However, careful coexistence schemes are needed to prevent LTE from conflicting hence degrading Wi-Fi transmission performance. There are mainly three coexistence mechanisms exist-

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ing: LTE blank subframe allocation, uplink power control, and listen-before-talk(LBT), while the last one is widely adopted and developed by LTE-U forum and later the 3GPP adopted solution licensed-assisted access(LAA). To analyze the performance of the chosen scheme, both simulation results and accurate analytical models are necessary.

In the early stage, research shows proof on why fair coexistence algorithms are needed to exploit unlicensed band for both LTE and Wi-Fi users. Anwer Al-Dulaimi et al. publish their simulation works [5] showing that Wi-Fi's throughput and end-to-end time delays performance declines severely with an LTE-U coexistence compare to traditional LTE. Hence, they move forward to propose four solutions for a fair transmission mechanism. These four solutions can be separated into two main domain: noncoordinated coexistence between LTE-U and Wi-Fi, and coordinated coexistence. Within the former, Adaptive LBT and Tunable Coexistence Gaps are introduced and discussed to be able to provide fair transmission under the unlicensed band. For the latter, the authors first propose the network function virtualization(NFV) interconnections to achieve a centralized cooperative control management for a fair sharing, then an extended EPC technology that uses x2 interface for ABS configurations. They introduce these four solutions for further study and explore for all practitioners.

Markov chain models have been used to evaluate Wi-Fi distributed coordination function(DCF) performance before [18], in 2014, Cheng Chen et al. [24] built on that when they adopted a simple investigation on a downlink coexistence scheme between LAA with LBT and Wi-Fi system. The authors apply Markov Chain models to calculate the downlink throughput. The numerical results show that LBT mechanism helps Wi-Fi performance under LAA and Wi-Fi coexistence scenario.

Later on in[31], Yuan Gao et al. constructed 3 Markov chain analytical models for Cat 4 LBT, Cat 3 LBT and Wi-Fi DCF respectively, and establish an evaluation framework in terms of throughput and transmission delay for LAA, Wi-Fi, and overall Wi-Fi-LAA networks performances. The results show that Cat 4 LBT LAA eNBs works the best when only regarding Wi-Fi performance and LAA LBT with fixed CW size outperforms LAA LBT with dynamic CW size when only regarding LAA system performance. This provides more proof to the existing simulation results and reminds LAA LBT schemes designers of the trade-off between wifi performance protection and LAA system performance.

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Another paper [55] looked into a very similar idea. The authors apply Ergodic Markov chain model to monitor the spectrum distribution of Wi-Fi and LTE regarding resources allocation efficiency. The results show that distribution probability converges after few iterations regardless of the initial conditions and LTE always ends up to utilize more channels with higher probability than Wi-Fi.

Recently, Yimin Pang et al. [67] conduct experiments to investigate the air time transmission sharing fairness between a duty cycle based LTE-U and Wi-Fi. The authors set up evaluation models based on multiple system parameters using probability theory and taking into consideration both strong and weak LTE-U interferences. Lastly, Monte Carlo random sampling procedure is adopted to yield enough numerical inputs to their models. The results show how parameters influence the fairness and performance of LTE-U and Wi-Fi systems: 1) The larger the duty cycle period for LTE-U, the less unfairness under both strong and weak interferences. 2) A duty cycle $\alpha \leq 0.3$ is the lowest value necessary for a fair air time sharing scheme, while a strong interference can enlarge α to a range of $[0, 1]$. 3) The sharing fairness degrades linearly with LTE-U to Wi-Fi collision probability q and the only possible collision occurs when LTE-U transmission starts after Wi-Fi transmission. 4) Similarly, the fairness also degrades linearly with the Wi-Fi payload length L . To conclude, simple coexistence schemes always results in unfairness towards Wi-Fi performance and hence better schemes are on high demands from researchers.

Another recent interesting project is done in[41] where the authors propose a new multi-game theoretic algorithm to model the resource allocation problem between LTE-U and Wi-Fi as a novel promising approach that needs further development. Under their multi-game framework, the authors proposed using two techniques: multi-game equilibrium(MGE) and multi-game stability(MGS), which is achieved by their two classes of algorithms. Regarding the experiment, the authors establish a three coupled game network consists of dual-mode BSs and WAPs that contend for 10 unlicensed bands, and many WUEs that pick Wi-Fi AP to maximize their rate. The resultant figures show that 1) WAPs throughput saturates slower in a multi-game model and hence result in a 50% higher sum-throughput than a previously used single-game model. 2) When the number of WAPs increases, the BSs sum-rate decreases. This implies that when Wi-Fi traffic increases, the amount of BSs offloaded traffic under unlicensed bands decrease. 3) The sum throughput of WAPs is much higher than a LBT strategy in a multi-game algorithm. Furthermore, the sum throughput

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can be improved until saturation by increasing the load in the network, while LBT's barely changes. Thus, more research is welcomed in applying promising game theory into LTE-U resource allocation problem. Better designed algorithms are required to improve the performance of LTE while also protect Wi-Fi users.

Researchers from Trinity College Dublin conducted a research topic to see whether LBT and CSAT, the two main coexistence mechanisms for Wi-Fi and LTE fairness, are working comparatively or not [20]. Based on this idea, the authors established a sample testbed upon a number of relaxable and non-relaxable assumptions. The results show surprisingly that when LBT or CSAT are used on LTE, the transmission throughput performance of Wi-Fi system remains the same with a certain configuration, but the one of LTE system is different instead. A similar result is obtained as well regarding transmission delay. According to the researchers, these interesting results they obtained still requires further understanding.

LTE-WiFi coexistence strategies can be majorly categorized into spatial multiplexing, frequency multiplexing based on channel selection, time multiplexing using duty cycling, LBT and ABS. Interference management has mainly focused on the downlink due to the asymmetric nature of traffic in LTE, in the order of 8:1 [64]. Mechanisms using Duty Cycling for coexistence are proposed in [21], [7], [88], [19], [73], [36] and [27] whereas, [77], [40], [54] and [53] explore other possible coexistence schemes, such as LBT. Additionally, [46], [74] and [17] use stochastic geometry in interference and coverage area modeling.

The mutual impact on the performance of LTE and Wi-Fi has been studied in [7], [36] taking the average throughput per user as a quality metric. Though [36] proposed a mechanism that is backward compatible with no mutual signaling, Wi-Fi must perform traffic sniffing to predict the ABS pattern. Moreover, the assumption that ABS periods are completely free of all interference limits its application. Two different solutions of Wi-Fi coexistence using ABS and interference avoidance are proposed in [88]. However, the coordinated interference avoidance here relies mostly on cell pairing or clustering, and assignment of priority among cells, which requires major modification of current standards. [19] proposed a relatively fair resource allocation method that formulates a convex optimization problem of minimizing LTE-U/Wi-Fi collisions. In [82], the authors provide a comprehensive survey of related works. It also presents theoretical models of throughput and overhead for coexisting methods. A framework that models the channel access of both technologies

Table 4.1: Coexistence Scheme Comparison

Category	Coexist scheme	LTE Modification	WiFi Modification	Coordination	Overhead	CRS
Duty Cycle	E-FI	No	Requires PSR	No	No	Yes
	E. Almeida[7]	Blank subframe	Dual coex modes			No
	H.Zhang[88]	Spectrum Sensing	Neighbor Discov.			
	C.Cano[19]	BS Monitors channel	No	No	No	N/A
	CSAT	Adaptive DC				
	N.Rupasinghe[73]	Q-Learning Adaptive DC				
	Z.Guan[36]	No	LTE packet sniffing	Yes	LTE	
LBT	T.Tao	Adaptive CW	No	Yes	No	N/A
	S.Haj-mohammad[40]	Fixed CW		No		
	F.Liu[54]	Dual bands		No		
	Y.Li[53]	Adaptive CW	Adaptive CCA th.			

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with LTE adopting the LBT approach is given in [77]. A fixed contention window is set in [40] that limits the performance of LTE in terms of user throughput when collisions occur with Wi-Fi devices. A dual band approach is proposed in [54], where LTE sends its control signals through the licensed band, and offloads data traffic onto the unlicensed band. However, this reduces the spectral efficiency of the system. Recently, the use of stochastic geometry for characterizing the interference, and modeling the coverage area and throughput in WLAN and LTE systems has gained traction [17]. In [46], a simplistic fluid network model is used to study the ideal coexistence scenario when no multipath and backoff is present. Device-To-Device (D2D) communications for LTE-Wi-Fi coexistence have been proposed in [71], [9] to increase the LTE throughput by offloading some of the messages to Wi-Fi Direct. A spatiotemporal estimation of interference and a load balancing mechanisms are proposed in [39] and [87].

Regulations in some markets (Europe and Japan) enforce additional unlicensed band access requirements defined as Listen Before Talk (LBT). For this reason R13-based LTE/Wi-Fi coexistence is proposed to unify the procedures for Unlicensed bands access in a single framework described as Licensed Assisted Access (LAA)

European LBT requirements are outlined in ETSI EN 301 893 and are used as a basis for LAA design. Which mainly defines an extended Clear Channel Assessment (eCCA) procedure. Load-Based Equipment (LBE) design uses enhanced CCA (eCCA) procedures and enables robust LAA operation to coexist with Wi-Fi in the same band as illustrated in the figure below. Note LBT alone is not sufficient to guarantee coexistence and fair sharing with Wi-Fi in all scenarios and additional scheduling techniques are needed.

In addition to LBT via CCA procedure, it is envisioned that Rel-13 LAA would modify existing DL and UL LTE waveforms, add discovery signals to support unlicensed band discovery and access, add beacon signals to reserve the channel for transmission following CCA success and modify HARQ protocol to support asynchronous operation.

3GPP approved LAA as a Rel-13 Study Item (SI) in September 2014. The SI scope covers both Supplemental DL (SDL) and DL/UL CA. The SI is expected to conclude by June 2015 followed by a Work Item. 3GPP Rel-13 completion is expected in the first half of 2016.

Qualcomm plans to showcase Rel-13 LAA SDL aggregation at MWC 2015. The demo uses multiple LAA prototype small cells and UEs based on Qualcomms proposal for LAA design,

which includes the new waveforms supporting LBT via CCA. While user experience and network capacity are increased by using LAA, co-channel coexistence and fair sharing with Wi-Fi is also showcased.

4.2 LTE/WiFi Coexistence Experimental Testbed

A testbed (depicted in *Figure 4.2*) is built to measure Channel Busy behavior under LTE interference in the 3 ABS modes (0,1 and 5). The Zedboard transmits LTE traffic generated using srsLTE[33], while the measurements are collected on the desktop computer hosting an AP and while connected to a client (the laptop).

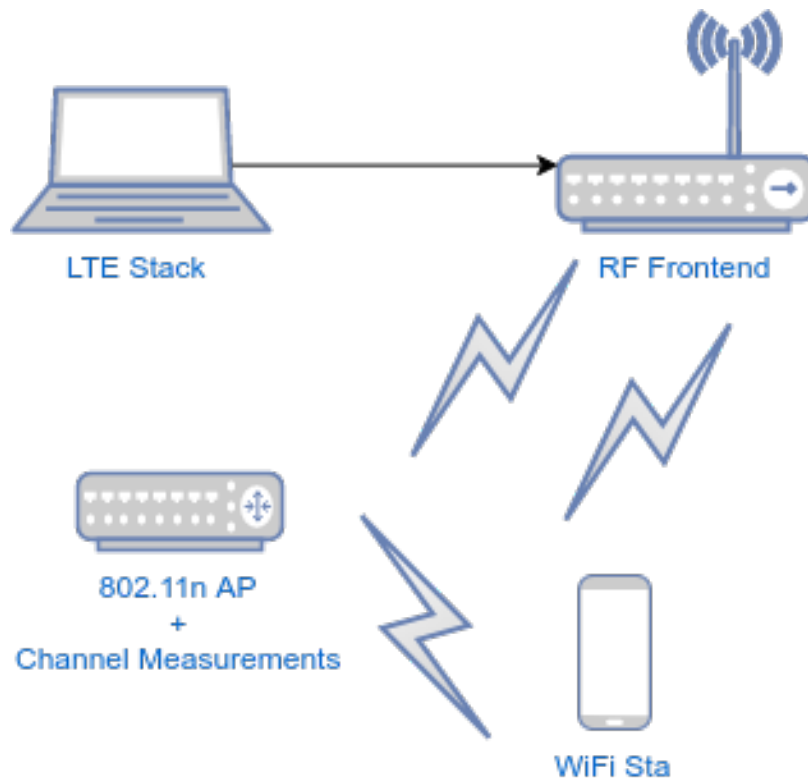


Figure 4.1

4.2.1 LTE Downlink signal

The open source project srsLTE provides a set of CPU optimized libraries supporting the creation and processing of LTE physical channels using modern CPUs and supporting hardware

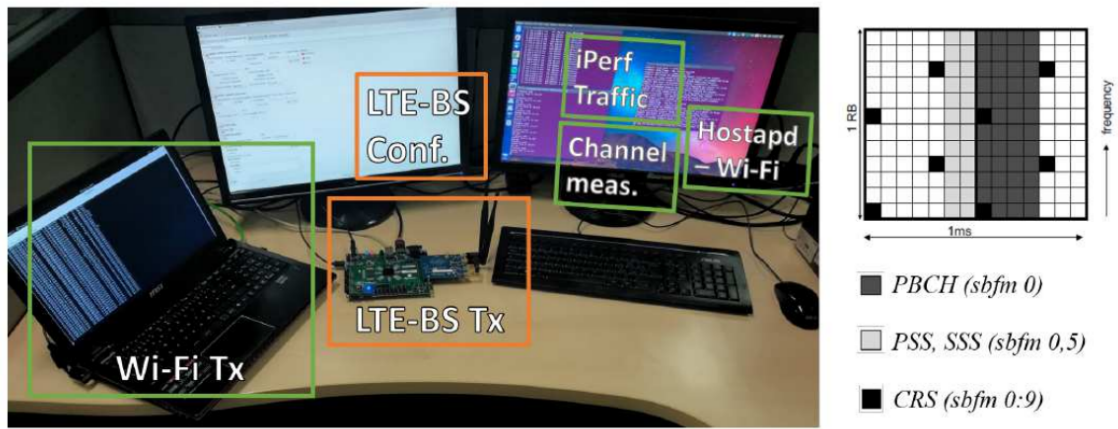


Figure 4.2

interfaces with various SDR platforms include the USRP b210 using in this testbed. We modified the included sample application *pdsch_enodeb* to support the generation of the three types of ABS of interest:

- ABS0: contains PSS, SSS, PBCH and CS Reference signals.
- ABS1: contains only CS Reference signals.
- ABS5: contains PSS, SSS and CS Reference signals.

For each ABS type we generate a downlink LTE traffic consisting of a continuous stream of padded subframes of that same ABS type. This will allow us to see the statistical behavior of the channel's availability to WiFi.

4.2.2 WiFi Channel Busy measurement

The Linux *cfg80211* and *mac80211* wireless APIs provide a template data structure that if properly filled should indicate statistics about channel access states and operations.

```

struct survey_info {
struct ieee80211_channel *channel;
u64 time;
u64 time_busy;

```

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```
u64 time_ext_busy ;
u64 time_rx ;
u64 time_tx ;
u64 time_scan ;
u32 filled ;
s8 noise ;
};
```

Where the structure elements of interest (time and time_busy) are defined as follows:

- time: the amount of time in ms the radio was turned on (on the channel).
- time_busy: the amount of time the primary channel was sensed busy.

As of now, the only Linux kernel driver that implements filling this structure is the Atheros cards drivers suite that includes the ath9k driver we are using.

The ath9k driver fills this information when ath9k_get_survey function is called by a userspace process. The statistics though, are first collected at ath_hw_cycle_counters_update that probes AR_CCCNT, AR_RCCNT, AR_RFCNT, AR_TFCNT hardware registers that act as an interface between the MAC state machine running on the SoC and the kernel driver, as shown in the following code snippet:

```
cycles = REG_READ(ah , AR_CCCNT) ;
busy = REG_READ(ah , AR_RCCNT) ;
rx = REG_READ(ah , AR_RFCNT) ;
tx = REG_READ(ah , AR_TFCNT) ;
```

The measurement used here is hardware cycles, a cycle's duration depends on the clock-rate used for the current configuration of the hardware, the conversion to seconds happens when ath_update_survey_stats calls ath_hw_cycle_counters_update.

```
struct ath_hw *ah = sc->sc_ah ;
struct ath_common *common = ath9k_hw_common(ah) ;
int pos = ah->curchan - &ah->channels[0] ;
```


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```
struct survey_info *survey = &sc->survey[pos];
struct ath_cycle_counters *cc = &common->cc_survey;
unsigned int div = common->clockrate * 1000;

if (ah->power_mode == ATH9K_PMLAWAKE)
ath_hw_cycle_counters_update(common);

if (cc->cycles > 0) {
survey->filled |= SURVEY_INFO_TIME |
SURVEY_INFO_TIME_BUSY |
SURVEY_INFO_TIME_RX |
SURVEY_INFO_TIME_TX;
survey->time += cc->cycles / div;
survey->time_busy += cc->rx_busy / div;
survey->time_rx += cc->rx_frame / div;
survey->time_tx += cc->tx_frame / div;
}
```

After this the survey statistics are ready to be consumed by `ath9k_get_survey`.

The behavior of the `ath9k` driver is in such a way that this cycle of updates provides updated results when the driver is put into action in a managed or AP mode attempting to utilize the channel. For instance, the values provided are erroneous when trying to use this functionality while the driver is in monitor mode. With that said, we put the driver in AP mode serving traffic to a connected client. Using `iperf` we generate downlink traffic from the AP trying to fill the MAC queues with outgoing traffic forcing the driver to always look for TX opportunities thus sensing the channel and updating the related survey measurements.

4.2.2.1 Results

Measuring Channel Busy % in Figure 4.3.

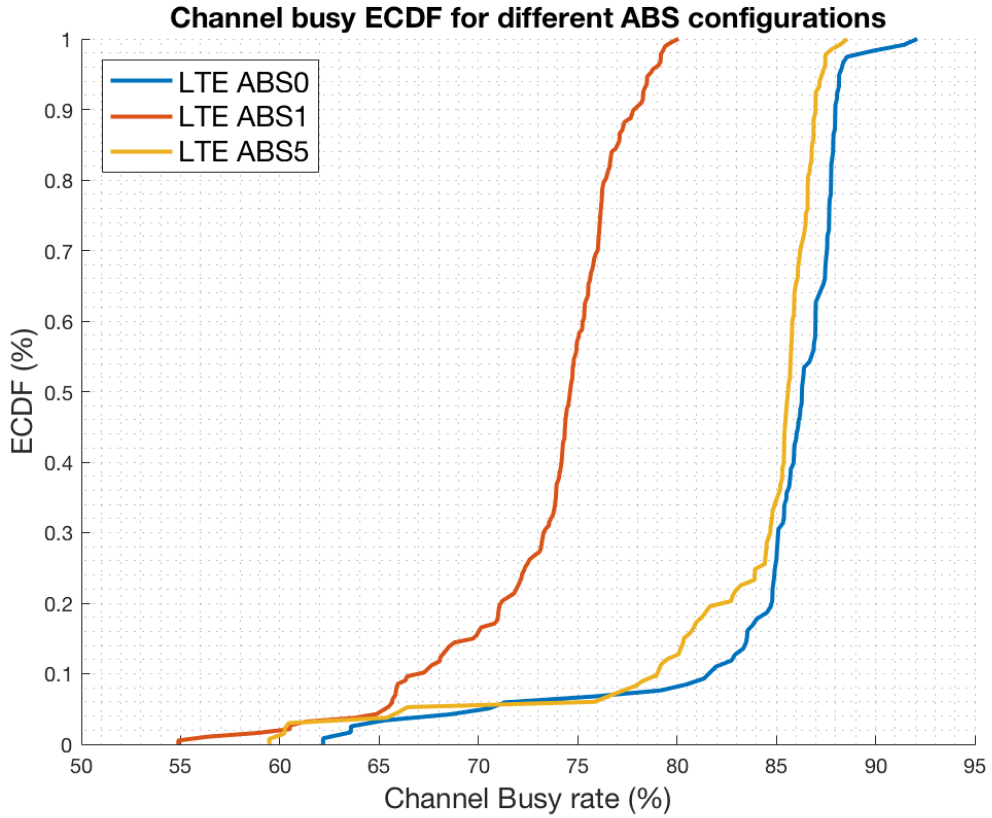


Figure 4.3

4.2.3 Measuring Time to TX

At packet arrival to the ath9k driver, without going into the details of how upper layer protocols are encapsulated at this level, we investigate the TX chain that the 802.11 frame passes on the way to transmission.

As can be seen in *Figure 4.4* the frame first passes by a queuing chain where starting at *ath9_tx* function that initializes the hardware and passes the frame pointer to *ath_tx_start* where further setup is performed but more noticeably frame aggregation is checked and scheduled if required. The packet queuing process ends at *ath_tx_txqaddbuf* the *ath9k_hw_txstart* is called. From here on, the packet is in the queue and the hardware will transmit it when the channel is available.

Upon successful hardware transmission to the air, this event will be signaled by setting the *ATH9K_INT_TX* interrupt and calling *ath_tx_complete* function, thus signaling the transmission

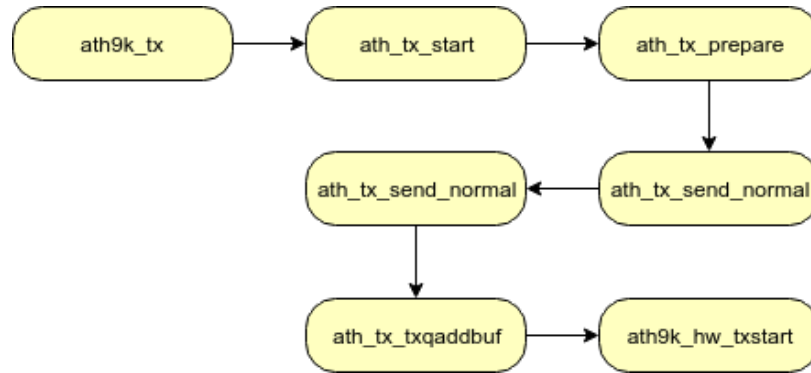


Figure 4.4

of a WiFi packet (Figure 4.5).

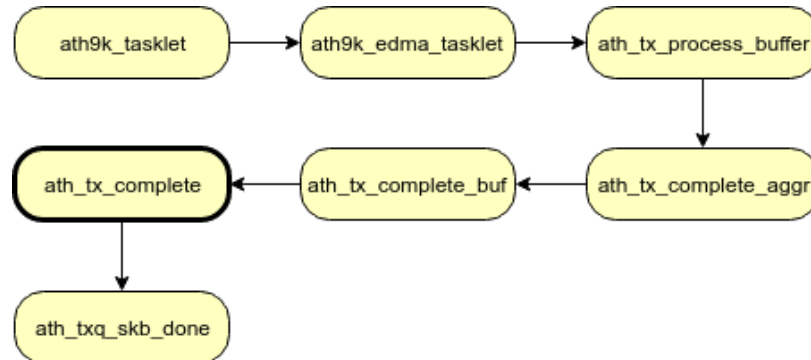


Figure 4.5

The basic course of actions the driver takes is to proceed to check if the channel is free, by channel sensing for a DCF Inter-Frame (DIFS) interval so it can carry on the transmission. If the channel is sensed to be busy, the behavior is then to defer the transmission until the end of the ongoing one after which it waits an extra DIFS interval and performs a backoff delay chosen randomly in the interval $[0, W - 1]$ where W is the contention window (CW). Now, when the DIFS+Backoff delay passes the transmission is attempted again if the medium is IDLE. In the case of ath9k, the previous procedure is programmed internally on the hardware without Linux driver access to different states and timely sensing results. Thus it was not possible to have direct timing information of how LTE generated interference affects the DCF behavior and the average inter-frame transmission delay (the average transmission delay between two successive transmissions). Our indirect approach takes advantage of the fact that when ath9k reaches ath_tx_complete_buf the

channel has been sensed IDLE and the node has waited for a DIFS and a random backoff.

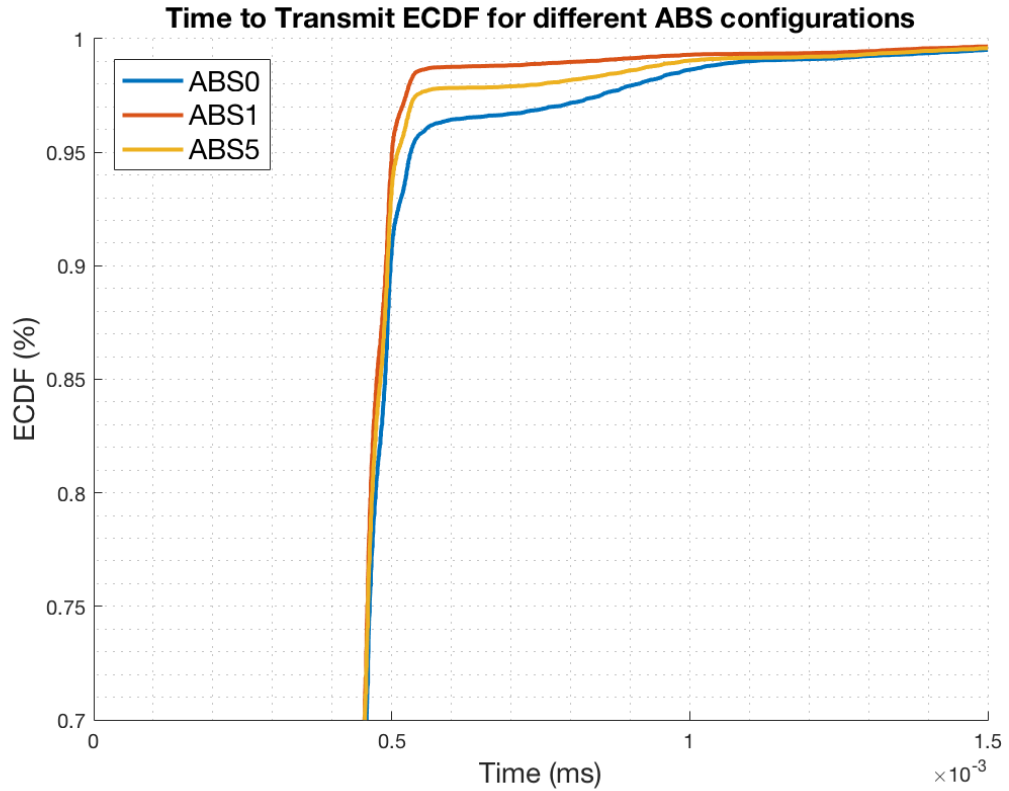


Figure 4.6

4.3 E-FI Project

4.3.1 Introduction

Our studies show that the simplistic assumption of a completely interference-free ABS does not hold true in practice, as the current LTE standards describe mandated and optional reference signals (called pilots henceforth, shown by shaded time-frequency grid units in Figure 1) within the ABS that has a significant impact on Wi-Fi. Release 11 includes further eICIC (feICIC), with mechanisms for LTE users to detect and cancel the signals from interfering cells. However, this capability is not present in Wi-Fi receivers. Release 13 describes Listen Before Talk (LBT), where LTE is expected to perform carrier sensing and backoff before capturing the ISM band channel.

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This proposal, however, has not been adopted in many key markets worldwide, including the U.S. Several prior works have relied on explicit feedback from the Wi-Fi access points (APs) to the LTE base station (BS) for sharing the medium. A differentiating aspect of our work is that the AP and the BS are unable to exchange information explicitly; in fact there is no coordination mechanism defined up to the latest, still-evolving LTE Release 14.

Our approach to use Wi-Fi Direct for relaying purposes is validated in studies like [10], improvements in throughput and energy consumption from D2D are shown ([75] and [37]).

E-FI design goals and operational overview: E-Fi empowers the Wi-Fi AP and its associated nodes to operate alongside LTE-U transmissions, without dedicated feedback to/from the LTE BS. Instead, it reuses pre-set LTE ABS patterns to schedule its transmissions. Our solution partitions the Wi-Fi network into self-organizing groups based on the observed PSR. The groups follow the Wi-Fi Direct standard, with the Group Owner relaying traffic to vulnerable nodes that are distant from the AP, but close to the LTE BS. Thus E-FI purely looks at the coexistence problem from the Wi-Fi perspective. Recognizing the practical difficulties in providing feedback to the LTE BS, as well avoiding the complexities of solving optimization problems, E-Fi presents an algorithmic framework that enables survival of the Wi-Fi network in uncooperative LTE-U deployments and rogue small-cell installations.

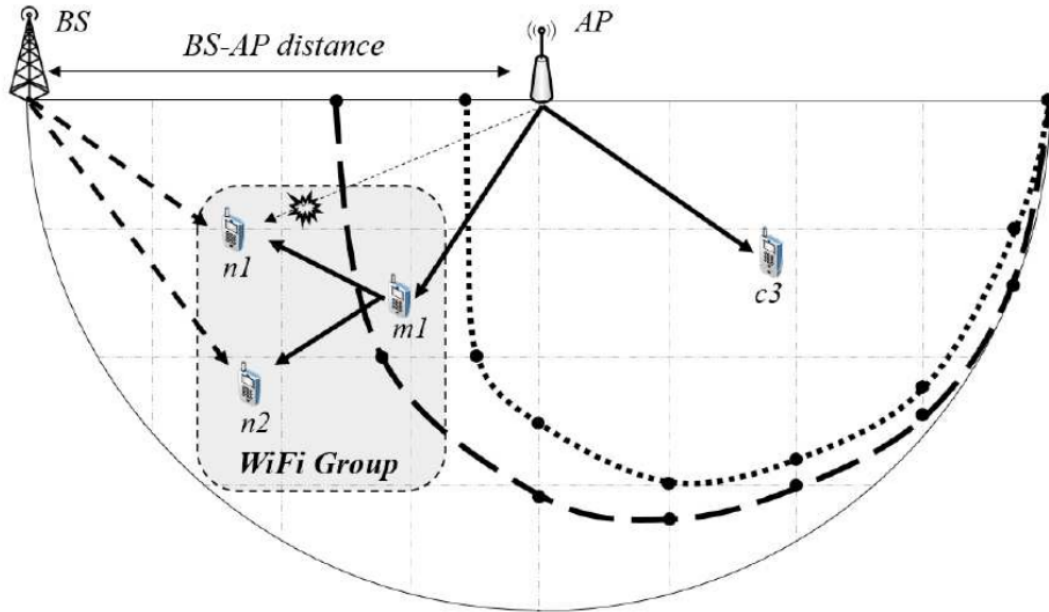


Figure 4.7: Example scenario showing impact of different ABS on Wi-Fi packet reception due to the control signals embedded in such frames. Wi-Fi coverage radius is chosen for 90% PSR and 17dBm transmitted power. The dashed and dotted lines define the coverage areas when subframe 1 and 0 are designated ABS, respectively, showing that different subframes allow varying spatial coverage for 90% PSR.

The operating principles of E-Fi rests on three observations:

- First, not all ABS offer equal transmission opportunities for Wi-Fi, as shown in the previous experimental test on the built testbed, depending upon where the ABS appears within the parent LTE downlink frame, i.e, its position in one or more of 0-9 subframes, it carries different types of pilot sub-carriers. This, in turn, requires varying number of committed resource units. A complete resource block is composed of a grid arrangement 168 such units, with:
 - 12 subcarriers along the Y (frequency) axis.
 - spanning 14 slots totaling 1ms along the X (time) axis.

For example, ABS 0 has significantly more presence of interfering pilos and offers reduced free channel access compared to others.

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- Second, as shown in the right-hand side of 4.2 , depending on both the specific ABS frame being considered and the separation between the LTE BS from the Wi-Fi nodes, there is a non-negligible impact on the carrier sensing and deferring process for the latter. The channel must be found empty for a combined duration of distributed inter-frame space (DIFS) and random backoff before transmission can begin. Thus, Wi-Fi nodes close to the LTE BS have considerably less chances to transmit a packet. This motivates our approach to schedule Wi-Fi groups into different ABS, thus reducing the number of devices contending for the channel.
- Third, SINR and hence BER) can be considerably improved by reducing the transmission distance, which motivates the approach of introducing relay nodes (e.g., m_1 in 4.7) operating on Wi-Fi Direct. The E-Fi module in the AP carefully assigns uplink and downlink durations (defined on the basis of whether traffic originates at the AP or the nodes) and forms Wi-Fi Direct groups based on reported PSR. Though remote nodes (e.g., n_1 and n_2) now forward their traffic to the AP and vice-versa using 2-hops, this overhead is compensated with high PSR for each link.

The main contributions of this work are:

1. We show that the assumptions in [21] and [7] that Wi-Fi has undisturbed channel access during the entirety of the ABS is a simplification that has practical impacts on coexistence.
2. Different from most approaches, we design E-FI under the assumption that the AP and the BS are unable to explicitly exchange information. We also do not introduce any changes to the LTE standard.
3. We undertake a systematic study on the impacts on Wi-Fi PSR and carrier sensing mechanism caused by various pilot signals in different ABS configurations through standard-compliant physical layer wave-form simulations.
4. We enable self-configuration of Wi-Fi nodes into Wi-Fi Direct groups with forwarding relays using PSR as a selection metric. We then propose a modified Hungarian algorithm with well-defined complexity instead of computationally expensive optimization techniques for the formation of such groups.

5. We formulate an ABS utilization strategy at the AP that partitions contention-based channel access time into distinct intervals, considering individual traffic loads and Wi-Fi Direct relay forwarding overheads.

4.3.2 Impact of ABS on 802.11 MAC/PHY Simulation Studies

The ABS pilots not only affect the Wi-Fi transmission in the downlink, which we quantitatively analyze through the PSR, they also impact the uplink transmissions by reducing channel access opportunities. To characterize this effect, we consider the scenario of a Wi-Fi device is continuously attempting to transmit under a continuous presence of ABS type of sub-frames. That is, the LTE received power always exceeds the carrier sensing threshold, leading the Wi-Fi device to backoff (Figure 4.16). We used the LTE/WiFi testbed described before, where we modified the srsLTE [28] implementation of the Downlink frames on a USRP B210 series as a way to saturate the channel with LTE frames under different ABS configurations. On the Wi-Fi side, a regular laptop equipped with an Atheros NIC emulated the behavior of an AP attempting to access the channel and operating in saturation mode. We used iperf [29] to generate Downlink traffic from the AP, aiming to fill the MAC queues with outgoing traffic and forcing the driver to always look for transmission opportunities.

The Linux 802.11 configuration API (cfg80211) provides a template data structure that contains the parameter `time`, measuring the time the radio is active, and `time busy`, measuring the amount of time the primary channel was sensed busy. The Atheros card was selected for this set of experiments since it is the only off-the-shelf NIC allowing access to these parameters by means of the `ath9k` driver[30].

4.3.3 Relays for Resilient Transmission during ABS Sub-frames

In this Section, we motivate the key strategy of elevating selected nodes to a relay position to counter the impact of the ABS pilots. These relay nodes forward traffic to and from the AP, connecting remote nodes affected by low PSR. E-FI requires such relays to become Wi-Fi Direct group owners, and by reducing the link distance in the presence of LTE pilots it improves the collective PSR of the network.

Consider a Wi-Fi AP connected to V nodes in its coverage area and represented by the set $\Omega_{Wi-Fi} = (v_1, v_2, \dots, v_V)$. An LTE BS serves U user equipment (UEs). The LTE BS can schedule a number of ABS independently of the Wi-Fi, and any such ABS pattern is valid for 40ms. Consider a subset Ω_{SZ} of M nodes that happen to be inside the safe zone ($PSR_j \geq PSR_{Th}, \forall j \in \{1, M\}$) and a subset (Ω_{NSZ}) of N nodes that happen to be outside it ($PSR_i < PSR_{Th}, \forall i \in \{1, N\}$). Therefore, $V = M + N$. Any device ($m_j, \forall j \in \{1, M\}$) within the safe zone, defined on the basis of PSR, is a potential relay candidate. Those nodes that are outside this range are non-safe zone nodes that attempt to associate with a distinct relay node. All data communication between the relays and such non-safe zone nodes occurs via Wi-Fi Direct within a given ABS. The traffic exchange between the relay and the AP occurs via regular 802.11 in a different ABS.

As we describe in next section, E-Fi distributes the available ABS for the two sets of nodes: *Set I* containing Wi-Fi Direct groups composed of both relays and non-safe zone nodes. *Set II* containing (i) non-safe zone nodes that are unable to connect to intermediate relays, and (ii) safe zone nodes that do not serve as relays. E-Fi further introduces differential backoff duration to ensure that the remote non-safe zone nodes in *Set II* (that suffer from lower PSR) get increased transmission opportunities to recover from likely higher errors.

4.3.4 Relay Selection and Device Grouping Algorithm

We formulate the Wi-Fi Direct group formation as a Generalized Assignment Problem (GAP), whose aim is to maximize the number of non-safe zone nodes connected to relays under the objective function of minimizing the average number of transmission in the downlink. Hence, this is the minimization version of GAP or MINGAP [23]. We choose this approach for two reasons:

1. Wi-Fi Direct standard allows a maximum number of 8 connections per group [6].
2. High PSR is desired per node in the downlink given the asymmetric flow of traffic. Hence, each group is owned by a relay ($m_j, j \in \{1, M\}$) that serves a set of associated non-safe zone nodes (Ψ_j). The cardinality of Ψ_j is denoted by $|\Psi_j|$. All nodes that are not in any relay-owned group are consolidated into *Set II* and represented by the variable Ψ_C that directly connects to the AP.

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The formal description of the problem is given in (1), where the objective function is to minimize the number of overall expected transmissions, subject to a maximum number of Wi-Fi device connections K per group and improved PSR for every node in the network compared to direct connection with the AP(2).

$$\min \overline{N_{tx}} = \min \sum_{j \geq 1} \left(\frac{1 + |\Psi_j|}{PSR_{n_i}^{AP}} + \sum_{i \in \Psi_j} \frac{1}{PSR_{n_i}^{m_j}} \right) + \sum_{i \in \Psi_C} \frac{1}{PSR_{n_i}^{AP}} \quad (4.1)$$

subject to:

$$PSR_{v_i}^* \geq PSR_{v_i}, \forall v_i \in \Omega_{W_i-F_i} |\Psi_j| \leq K, \forall j \in \{1, M\} \quad (4.2)$$

Here, $PSR_{n_i}^{AP}$, $PSR_{n_i}^{m_j}$ and $PSR_{m_j}^{AP}$ represent the estimated PSR for the direct transmissions by the AP and received at the non-safe zone node, the PSR for transmissions by the relay and received at the node and direct transmissions by the AP and received at the relay, respectively. Other terms are defined earlier. To ensure that the group formation has bounded complexity this organization into groups is undertaken centrally at the AP using a modified version of the Hungarian Algorithm [50] which allows for solving the MINGAP problem in polynomial time. It uses the PSR collected at the individual nodes and considers all possible non-safe zone node to relay associations from the device discovery phase from Wi-Fi Direct.

4.3.4.1 Device Discovery and PSR Exchange

As the first step, all nodes measure their expected individual PSR (using SINR and received power from AP, see Figure 4.7) that allows them to self-determine whether they lie in the safe zone. This allows early assigning of network roles. as opposed to a late-stage network reorganization using measured PSR. Any node in this zone is a potential relay and assumes the role of a Wi-Fi Direct group leader. It then begins the device discovery process by issuing discovery beacons and logs all non-safe zone nodes that initiate connection requests. Similarly, a given node i that identifies itself to be in the non-safe zone, will send reply beacons containing its ID, the estimated PSR for direct transmissions by the AP, i.e., $PSR_{n_i}^{AP}$, and the estimated PSR for the short-range link between itself and the relay candidate $PSR_{n_i}^{m_j}$. All potential relays also compute their estimated PSR for AP's transmissions i.e., $PSR_{m_i}^{AP}$, as this is the metric used to identify which nodes are in safe/non-safe zones.

4.3.4.2 Forming Initial Relay Groups

On receiving a set of replies from non-safe zone nodes, the candidate relay m_j determines which neighbor node i would experience improved PSR through a 1-hop Wi-Fi Direct-based relaying versus direct AP communication.

1. First, using the measurement of the received power from the non-safe zone nodes, it calculates the new SINR and computes the PSR of the link between itself and the non-safe zone nodes ($PSR_{n_i}^{m_j}$).
2. Second, it checks if the expected number of transmissions through the 1-hop communication (w_{ij}^*) is lesser than the direct one to the AP (w_i) for that node as

$$\frac{\overbrace{1}^{w_{ij}^*}}{PSR_{m_j}^{AP}} + \frac{1}{PSR_{n_i}^{m_j}} < \frac{\overbrace{1}^{w_i}}{PSR_{n_i}^{AP}} \quad (4.3)$$

The subset Φ_j contains non-safe nodes i ($i \in \{1, N\}$) that meet this condition for relay $m_j \in \{1, M\}$, and hence, benefit from association with it. Each candidate relay node j creates a vector of PSR estimates y_j that includes its own $PSR_{m_j}^{AP}$ as well as the effective PSR w_{ij}^* estimated for the non-safe zone nodes $i \in \Phi_j$ that associate with it as follows

$$y_i = \left[PSR_{m_j}^A, w_{\alpha j}^*, w_{\beta j}^*, \dots, w_{\gamma j}^* \right] \forall \alpha, \beta, \gamma \in \Phi_j \quad (4.4)$$

This vector is sent to the AP by all the candidate relays. The final group formation is completed at the AP using a modified Hungarian Algorithm (SECTION). The individual group membership is then relayed back to the network by the AP.

4.3.4.3 Forming Final Groups at the AP

Consider the set of vectors representing PSR measurements reported by all the candidate relay nodes to the AP, i.e., $(y_i, \forall j \in \{1, M\})$. It is possible that the same non-safe zone nodes occur in multiple tentative groups formed by the candidate relays. Wi-Fi Direct requires each node to be linked to only one group owner. Hence, the goal of this stage is to (i) finalize the groups such that the nodes connect to one relay only, and (ii) distribute nodes uniformly throughout the groups within the network to maximize the overall PSR. For this purpose, we use a modified Hungarian Algorithm that matches nodes to relays using the PSR vector described above.

Algorithm Description

The AP builds an $N \times (M + 1)$ matrix \mathbf{W} containing the measurements vector $x_j, \forall j \in \{1, M\}$, forwarded by N candidate relays [88] as well as the initial PSR values ($w_i, \forall i \in \Omega_{W_i-F_i}$). Given that the cardinal of the set Θ_j may vary for different m_j , the AP assigns 0 for the situations where (i) there exists no connection between the relay and the non-safe zone node, or (ii) the multi-hop forwarding is not beneficial for that node (i.e., $w_{ij}^* = 0 \forall i \notin \Phi_j$). Along the same lines, a matrix P is defined as $P = \lim_{n \rightarrow \infty} [1 - (1 - W)^n]$. The matrix P contains 1's if the relay communication between m_j and i is beneficial ($w_{ij}^* > 0$) and 0's otherwise ($w_{ij}^* = 0$).

$$W = \begin{matrix} & m_1 & \cdots & m_M & AP \\ \begin{matrix} n_1 \\ \vdots \\ n_N \end{matrix} & \left(\begin{array}{ccc|c} w_{11}^* & \cdots & w_{1M}^* & w_1 \\ \vdots & \ddots & \vdots & \vdots \\ w_{N1}^* & \cdots & w_{NM}^* & w_N \end{array} \right) \end{matrix} \quad (4.5)$$

We define the vectors $z = P \cdot 1$ and $t = 1^t \cdot P$. The former one shows the number of favorable connections for a given node, whereas the latter one shows the number of favorable connections that each relay m_j can offer. In other words, t shows the cardinal of $\Phi(t_j = |\Phi_j| \forall j \in \{1, M\})$.

We model the network as a Bipartite Graph $G = (C, S, W)$, where the set C contains the non-safe zone nodes (Ω_{NSZ}) and the set S contains the candidate relays (Ω_{SZ}) and AP. Recall that the weight of the edge from node n_i ($i \in C$) to relay m_j ($j \in S$) is w_{ij}^* and that to the AP is w_i . The group formation problem is solved using the Hungarian Algorithm [50], which finds the optimal matching to return the maximum PSR for the entire network. Thus, every node in set C is linked to one node in set S , and after the match, it is removed from the set C . Given that relays can forward traffic to/from more than one node, a modified Bipartite Graph G' is formed by adding dummy relays and APs so that a perfect match can be found. The algorithm terminates when C is an empty set or when no further matches are possible in a given iteration.

Note that all non-safe zone nodes that could not associate with a relay are automatically included in Ψ_C , i.e., the set of all nodes that are not in any relay-owned group. All candidate relay nodes that were not matched with at least one non-safe zone node are also included in Ψ_C . The

Table 4.2: Conditions under which Dummy nodes need to be added to the Bipartite Graph G' . K = maximum number of Wi-Fi Direct nodes. M relays and N non-safe zone nodes.

	$M \cdot N$		$M \cdot K = N$		$M \cdot K > N$	
	m'_j	AP	m'_j	AP	m'_j	AP
$\forall i, j, i \neq j, s.t.$ $\Phi_i \cap \Phi_j = \emptyset$	✓	✓	×	×	✓	×
$\exists i, j; i \neq j, s.t.$ $\Phi_i \cap \Phi_j = \emptyset$	✓	✓	✓	×	✓	n

multiple groups formed through the matching algorithm compose *Set I*. We show next how the AP distributes the ABS for both these categories of nodes based on network loads.

Algorithm Complexity

The Hungarian Algorithm has polynomial complexity given by $O(n^3)$. Although a simplistic solution to form G' would involve adding $(K - 1) \cdot |S|$ dummy relays and $(K - 1) \cdot |S|$ dummy APs to the set S to force the matching, this drastically raises the complexity to $O((2 \cdot K \cdot |S|)^3)$. Instead, E-FI intelligently adds dummy nodes when needed.

Table 4.2 shows the conditions under which it is necessary to add dummy relays or AP nodes in G' based on the 3-tuple (M, K, N) and the candidate sets Φ with the purpose of minimizing the complexity. Vector t shows the number of nodes that need to be inserted in the modified graph for each node in S . The maximum cardinality of set S is $1^t \cdot P \cdot 1$. A simplified scenario is shown in Figure 4.8 where groups are formed using the modified Bipartite Graph G' . Table 4.2 shows the need to add two dummy relays (m'_1 and m'_2) and dummy APs (m'_0 and m''_1). The number of dummy nodes is given by $t(t_1 - 1$ for $m_1, t_2 - 1$ for m_2 and $t_{M+1} - 1$ for m_0).

4.3.5 ABS Resource Distribution Algorithm For Groups

E-Fi adopts the strategy of fair resource sharing, wherein the AP assigns ABS to individual groups. Further, this resource allocation is done per group and also split between downlink and uplink. The short window of transmission opportunity within the ABS frames works only under conditions of limited contention between nodes. We define the downlink duration for transfer of data traffic from the AP to relays or to their associated nodes (i.e., $AP \rightarrow m_j$ or $AP \rightarrow m_j \rightarrow n_i$)

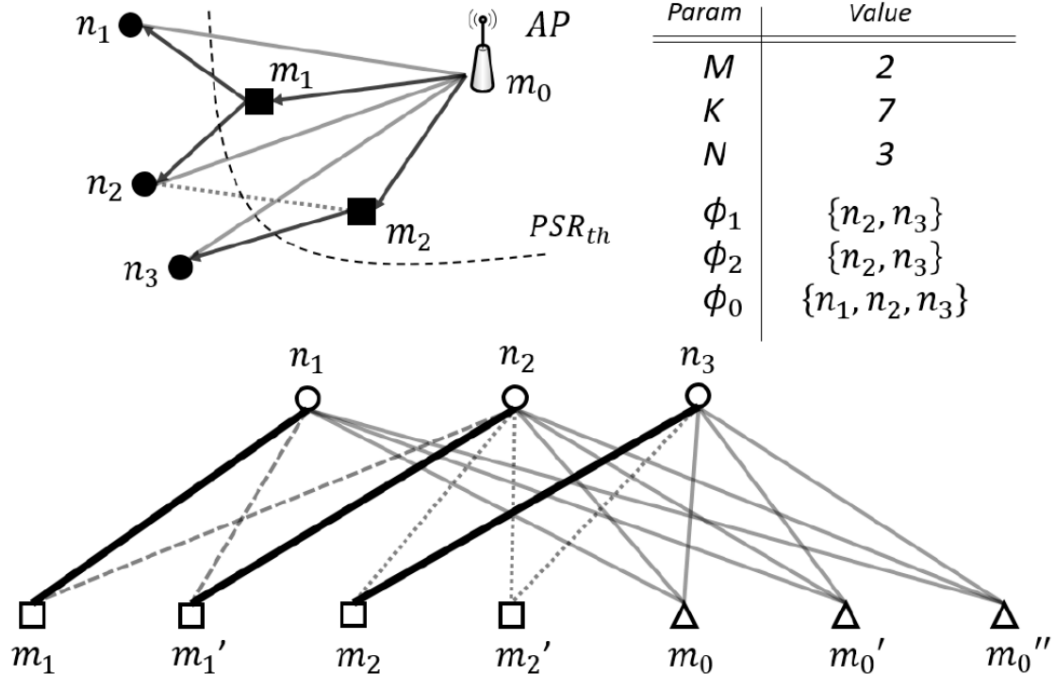


Figure 4.8: Modified Bipartite Graph G' given 3 non-safe zone nodes ($N = 3$), 2 candidate relays ($M = 2$) whose number of Wi-Fi Direct connections are limited by standard ($K = 7$). The final matching is shown in bold, where all the clients (G') are connected to exactly one relay/AP (bottom in G')

and also corresponding ACKs that traverse the links in the reverse directions. On the other hand, the uplink duration is for data packets originating from the relays or associated nodes with the AP as the destination. The ACKs in this case also arrive in the opposite direction within the same window of transmission. It is possible that a relay may not have sufficient time to forward data packets that it receives within the same ABS window. In such cases, the relay packet queue grows and transmission resumes the next time the group is assigned the ABS. The contention mechanism within a group is explained in detail later in next section.

E-Fi defines a load factor for every group j , denoted by η_j , as a weighted expression of w_{ij}^* (4.3) of (i) number of nodes in the group Ψ_j and the application load λ_i and μ_i , representing the throughput desired in the downlink (4.6) and uplink (4.6), respectively. For *Set II*, which contains the individual nodes (Ψ_C), we set $w_j = 1$ in the above equations (we assume the AP itself is

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sufficiently spaced from the LTE BS and not affected by the LTE interference) and $\lambda_{m_j} = 0$, $\mu_{m_j} = 0$ (no relay is present).

$$\eta_j^{DL} = \lambda_{m_j} \cdot w_j + \sum_{\substack{i \text{ s.t.} \\ n_i \in \Psi_j}} \lambda_{n_i} \cdot w_{ij}^* \quad (4.6)$$

$$\eta_j^{UL} = \mu_{m_j} \cdot w_j + \sum_{\substack{i \text{ s.t.} \\ n_i \in \Psi_j}} \mu_{n_i} \cdot w_{ij}^* \quad (4.7)$$

4.3.5.1 Inter-ABS Resource Allocation

Each LTE frame has a number of included ABS subframes. Through the Wi-Fi AP cannot influence this number, via feedback to the LTE BS, in E-Fi it can recognize the ABS pattern and know when such ABS are scheduled. Let the corresponding vector that indicates the presence of the ABS locations within the LTE frame be given by A , with number of such ABS represented by $|A|$. For instance, $A = [1100001100]$, where 4 subframes are designated ABS in the LTE frame. The AP assigns resources to the groups proportional to the load factor in the Downlink (4.9) and Uplink (4.8).

$$|A|_j^{UL} = \frac{\eta_j^{UL}}{\sum_{j \geq 1} \eta_j^{UL} + \eta_C^{UL}} \cdot |A|^{UL} \quad (4.8)$$

$$|A|_j^{DL} = \frac{\eta_j^{DL}}{\sum_{j \geq 1} \eta_j^{DL} + \eta_C^{DL}} \cdot |A|^{DL} \quad (4.9)$$

4.3.5.2 Intra-ABS Resource Allocation

In this Section, we explain how E-Fi handles collisions and medium contentions within the ABS frame such a frame can be allotted for either uplink or downlink and we separately consider both these situations. The key idea here is that each device uses a slightly shifted carrier-sensing start time while accessing the channel depending upon the number of packets in its MAC layer queue and the reliability of the links (PSR). This time shift results in preferential access to the channel for certain stressed nodes who experience growing queues (such as relays) and distant nodes with low PSR (such as non-safe zone nodes without relays).

Downlink

Both the AP and the relay of a group contend for the channel. If the former wins the contention, then the destination is the relay. If the relay wins, then it begins to forward the queued packets to its associated (and downstream) Wi-Fi Direct group members. Through a control parameter α , E-Fi ensures that (i) the AP has enough opportunities to successfully transmit the packets to the relays (link l_1) according to the application load demanded by the Wi-Fi Direct nodes (4.10) and (ii) relays have priority to forward the packets from the AP to the respective Wi-Fi Direct nodes (link l_2) as soon as they receive them (4.11). These conditions provide an upper and lower bound for α (4.12) as follows:

$$\overbrace{\lambda_{m_j} + \sum_{i \in \Psi_j} \lambda_{n_i}}^{\lambda_j} \leq \frac{T_j \cdot \alpha}{T_{tx} \cdot w_j} \quad (4.10)$$

$$\frac{T_j \cdot \alpha}{T_{tx} \cdot w_j} \leq \frac{T_j \cdot (1 - \alpha)}{T_{tx} \cdot \overline{w_{ij}^*}} \quad (4.11)$$

$$\lambda_j \cdot \frac{T_{tx} \cdot w_j}{T_j} \leq \alpha \leq \frac{w_j}{w_j + \overline{w_{ij}^*}} \quad (4.12)$$

Where, $T_j = |A|_j^{DL} \cdot 1ms/40ms$, and 40ms is the duration for which a given ABS pattern is active. $\overline{w_{ij}^*}$ is the average PSR in a cluster. Moreover, T_{tx} is the expected time for a successful packet transmission with no collisions. This parameter depends on the exponential backoff time, and PKT, which is the time to transmit a packet. The probability that the AP or the relay gets to transmit is given by α and $(1 - \alpha)$ respectively, (Note that $\alpha = 1$ for *Set II*) and allows for modifying both the duration of DIFS and the contention window as:

$$\begin{aligned} DIFS_{m_j \rightarrow n_i} &= (1 - \alpha) \cdot DIFS \\ CW_{m_j} &= (1 - \alpha) \cdot CW \\ DIFS_{AP \rightarrow m_j} &= \alpha \cdot DIFS \\ CW_{AP} &= \alpha \cdot CW \end{aligned} \quad (4.13)$$

Uplink

The uplink consists of two different situations that arise for nodes in *Set I* and Ψ_C . Consider nodes in *Set I*, where a relay j and its associated devices $|\Psi_j|$ contend for the channel. E-Fi gives priority to the relay to forward the packets from the Wi-Fi Direct nodes to the AP (4.11). Thus, the equation

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4.10 is valid with $w_j = 1$ (as the PSR from the relays to the AP is assumed to be 100%) and w_{ji}^* remains the reverse-path PSR in the UL. For the nodes that belong in Ψ_C and form the *Set II*, the individual devices outside of the safe zone also contend with others within the safe zone.

From 4.2, we see that the first column of the ABS always carries pilots that may also cause the Wi-Fi clients closer to the LTE BS to persistently backoff, while the ones within the safe zone (and hence farther from the BS) may discover the channel to be free. To address this inequality at both PHY and MAC layers, E-Fi defines a time shifted window for the safe-zone nodes. All nodes that are in the safe zone and a member of *Set II* must wait for 1 resource unit time from the start of the ABS before starting the DIFS. There is no such wait period imposed on the non-safe zone nodes. The intuition here is to give the nodes with low PSR additional opportunities to transmit within the ABS and bring about some measure of fairness in the link throughput for each node. We evaluate this design decision using Jains fairness index in next Section.

4.3.6 Performance Evaluation

We evaluate E-Fi using an integrated MATLAB and NS-2 simulation environment. MATLAB is used to model the signal waveforms at the PHY layer that are 100% standards-compliant using WLAN and LTE System toolboxes. This allows studying interference caused by LTE on a per-resource unit basis for various separation distances of Wi-Fi nodes. The spatiotemporal interference map is then imported into the NS-2 simulator, where we simulate the Wi-Fi Direct group formation and E-Fis enhanced channel access mechanism.

We first characterize the optimum range of PSR threshold to perceive the maximum improvement from E-Fi for several AP-BS distances. Since our approach does not have any topology restrictions, the improvement introduced by E-Fi is studied as a function of the distance between the AP- BS. Since the E-Fi performance is tightly related to the number of devices that can serve as relays, we evaluate E-Fi performance for several network densities, within a realistic range for a commercial Wi-Fi deployment. The simulations performed in this section consider 17dBm to be the transmit power for both Wi-Fi-AP and BS-LTE, which is the maximum transmit power allowed by the FCC for indoor communications. Furthermore, the initial coverage area is selected as for to provide 90% PSR when no LTE interference is present. Commercial deployments require PER levels within the range of 10-30% to provide reliable and uninterrupted communication without affecting

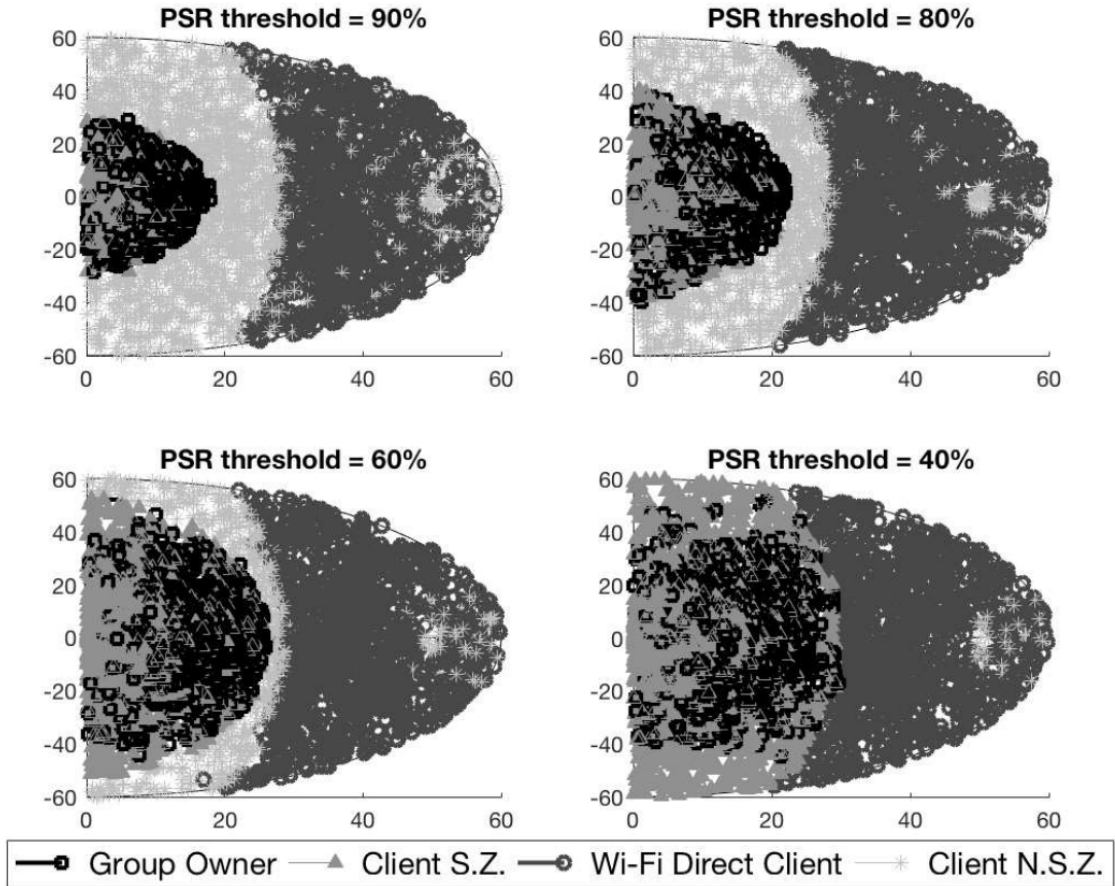


Figure 4.9: Node categorization and distribution in the coverage area when different PSR threshold are selected. The Wi-Fi AP is located at (0,0) and the LTE BS at (60,0).

the user experience. For space reasons, we report only the results referred to as downlink traffic scenario, i.e. the AP generates equal Constant Bit Rate (CBR) traffic for all Wi-Fi nodes given by λ pkts/s . Let T_{share} be the temporal share of the channel usage between the LTE and the Wi-Fi network, depending on how many ABS frames are included (it is impossible for Wi-Fi to operate in LTE data frames). Since E-Fi works in uncooperative LTE deployments, the value of T_{share} is assumed as an input parameter.

4.3.6.1 PSR Threshold Selection in E-Fi

The Safe Zone, directly defined by the PSR threshold, determines the number of nodes that could become Group Owners. As the PSR threshold decreases, more devices could meet the criteria and be elected as a Group Owner by the AP. Figure 4.9 shows how the PSR threshold determines the relay roles, and defines the regions outside the Safe Zone where nodes are most likely to be assigned a relay to increase their PSR. As the PSR threshold decreases, the Safe Zone area widens and more devices are categorized as Group Owners. This also reduces the number of nodes outside the Safe Zone that cannot be relayed. Also, Figure 4.9 shows that the devices elected as W-Fi direct clients are the ones closest to the LTE-BS, and thus suffering from severe interference. However, there is a small set of nodes, the closest one to the BS, for which E-Fi cant find an improvement given the high levels of interference.

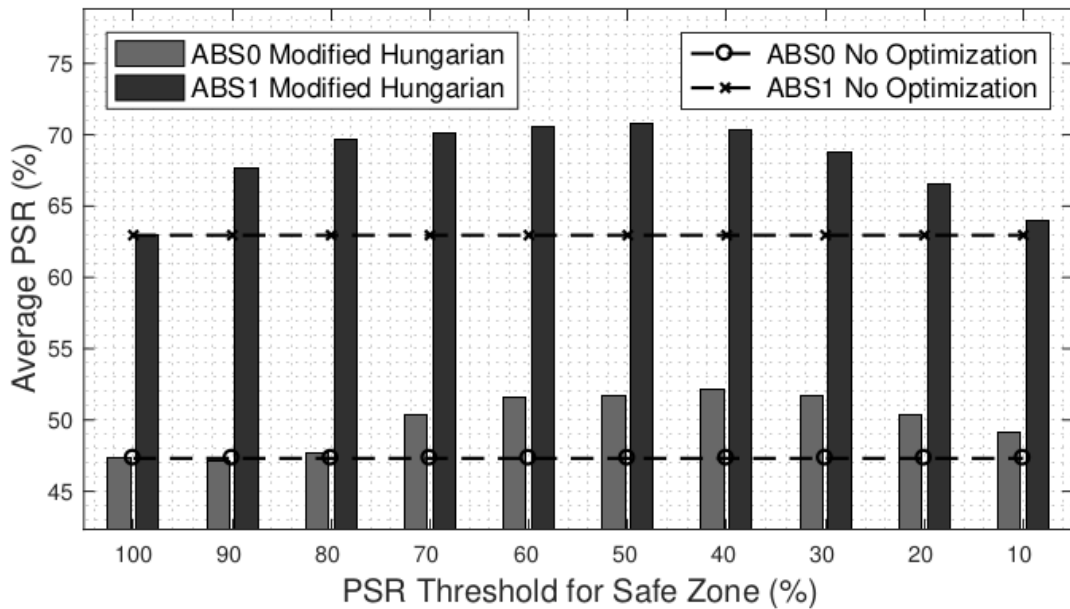


Figure 4.10: Average PSR of the Wi-Fi devices when several PSR thresholds are selected defining the Safe Zone. The optimum value lies between 70% and 40%

Figure 4.10 shows the optimum value for the PSR threshold so that E-Fi provides the maximum PSR. The optimum range is defined as the one that provides the highest average PSR for the considered AP-BS distance. The modified Hungarian Algorithm finds the maximum average

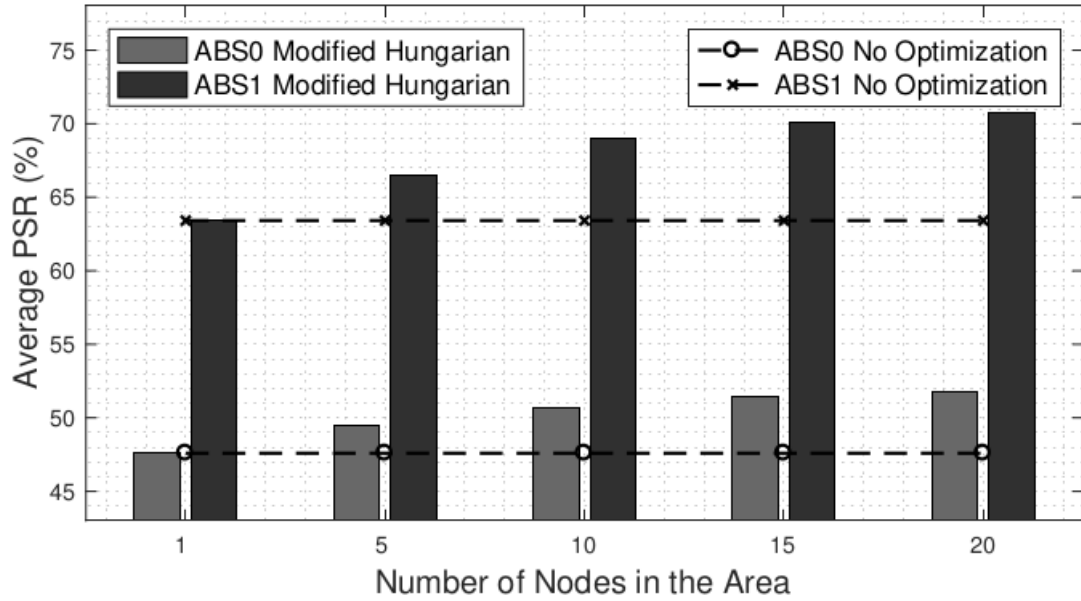


Figure 4.11: Average PSR of Wi-Fi devices when different Wi-Fi devices are deployed in the network. The PSR threshold is chosen to be 70%. E-Fi always improves the PSR and achieves a maximum of 10% improvement.

PSR when the threshold is selected within the range 40-70%, where the AP has enough Group Owners and nodes with low PSR that lie outside the Safe Zone become Wi-Fi Direct Clients.

4.3.6.2 Impact of the distance between the AP and BS

Since we consider the transmit power to be fixed to the maximum, we evaluate E-Fi's performance for different AP-BS distances. Figure 4.13 depicts the range where the maximum improvement is reached. As expected, when no LTE interference is present, the average PSR converges to the initial PSR threshold defining the coverage area.

4.3.6.3 Impact of the number of Wi-Fi devices

E-Fi relies on a certain number of nodes perceiving high PSR so that by enabling relaying capabilities, the PSR of other nodes can be increased. Figure 4.11 shows the PSR change as the number of nodes increases. Note that the increasing trend is because the PSR metric does not

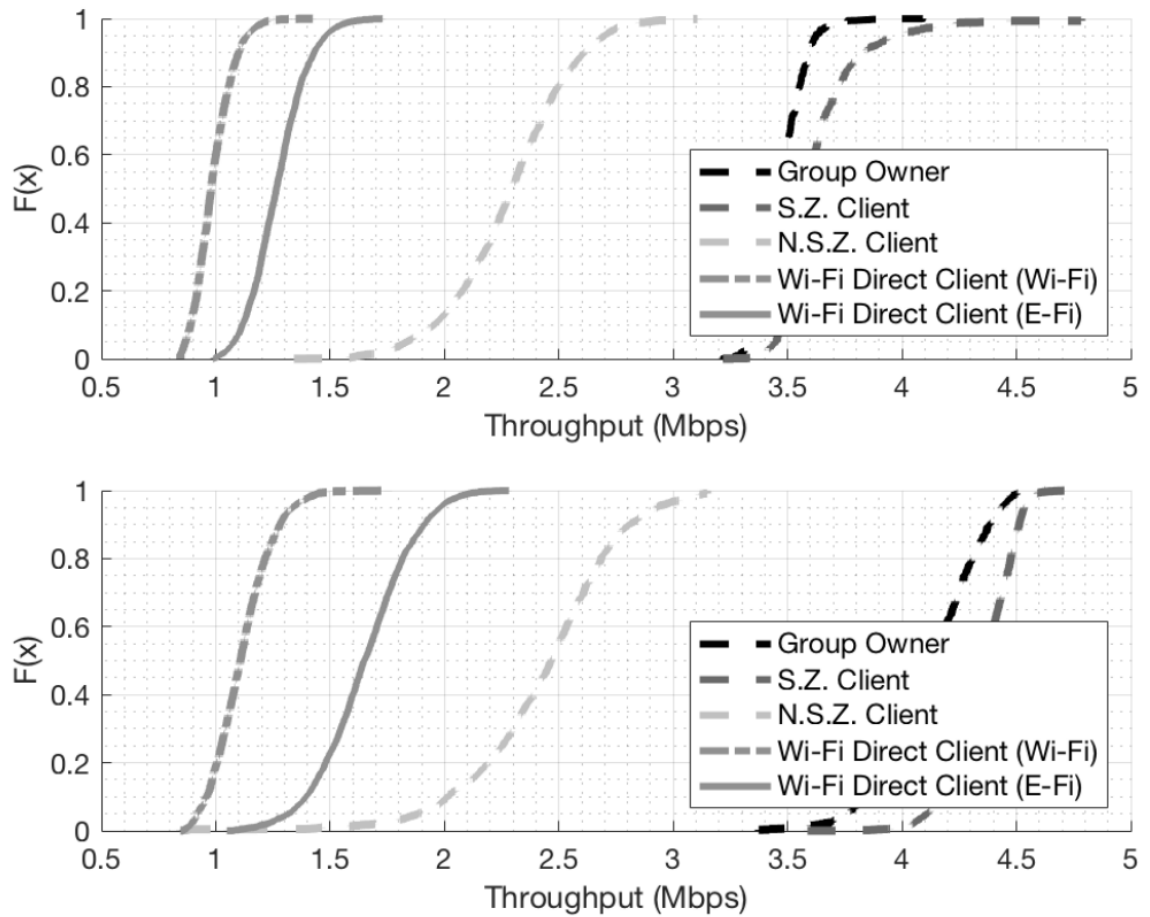


Figure 4.12: CDF of the Throughput of the Wi-Fi devices when 20 devices are operating in the network, the PSR threshold is chosen to be 70% and the BS is located 60m far from the AP. E-Fi improves the PHY throughput of the Wi-Fi Direct Clients 50-70%.

consider the impact of the channel availability or collisions, but it just accounts for the reliability of the link against LTE interference.

4.3.6.4 Throughput improvement introduced by E-FI

Next, we evaluate the improvement on the average PHY throughput that Wi-Fi Direct clients perceive by employing relaying capabilities. Figure 4.12 shows the throughput distribution for a network where 20 Wi-Fi devices operating within the coverage area being interfered by an LTE-BS located 60m far from the AP. The PSR threshold is chosen to be 70%. We note few key

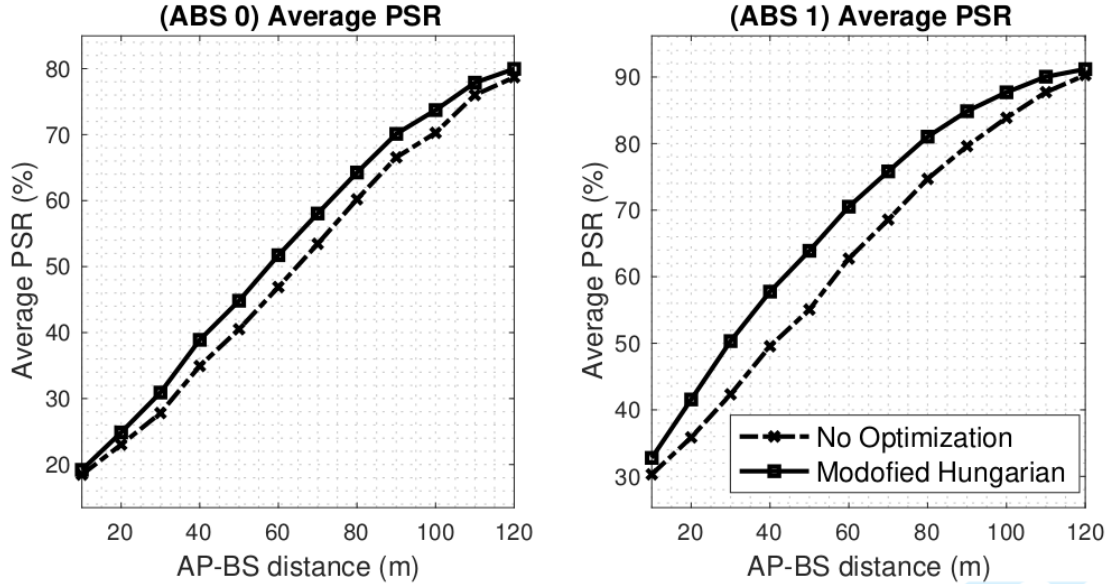


Figure 4.13: Average PSR of Wi-Fi devices for different AP-BS distances. The Wi-Fi devices are deployed within the initial Coverage Area, defined to be 90% PSR with no LTE interference. The PSR threshold is chosen to be 70%. E-Fi proves to provide the highest improvement when the BS is located 20-80 meters far from the AP.

findings: First, E-Fi introduces 50-70% improvement on the throughput of the nodes affected by the LTE interference. Second, the Group Owners tend to have lesser PSR than the Safe Zone Clients, meaning they are located closer to the Safe Zone boundary. Third, E-Fi helps the devices that are most affected by the LTE interference.

4.3.6.5 Benefits of Traffic Forwarding via Relays

We next evaluate how relays improve the application layer Packet Delivery Ratio (PDR) by comparing five different schemes with modular enhancements:

- LTE OFF, Legacy Wi-Fi. The WiFi nodes experience no LTE interference during an ABS. This is the typical assumption used in existing works, which we use for baseline comparison.
- LTE ON, Legacy Wi-Fi. Wi-Fi nodes experience LTE interference during the ABS, exactly calculated using MATLAB generated waveforms. This case corresponds to the realistic scenario that will occur in field deployments.

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- LTE ON, Random relay selection over all nodes. The relay selection and group member association with relays are performed in a pure random way.
- LTE ON, Random relay selection over the Relay Candidate (RC) set. The set of relay candidates is created according to (3), pairing non safe zone Wi-Fi nodes to the relays in a random way.
- LTE ON, Hungarian-based relay selection. Relay selections and node allocations are performed according to the modified Hungarian algorithm present in E-Fi.

Figure 4.14(a) shows the average PDR when varying the number of Wi-Fi nodes (N) in the network. Here, λ is set to 25 pkt/s, while T_{share} is 50%, i.e. the LTE and WI-FI networks have equal share of the channel. We can notice that the LTE OFF case overestimates data delivery without capturing packet losses. Instead, the legacy Wi-Fi incurs up to 60% of packet losses for $N=20$, due to:

- i channel errors caused by the BS interference or
- ii buffer overflow at the AP, due to the (likely) longer MAC re-transmissions for each packet

The pure random selection scheme worsens the situation, since the selected relays may provide lower link quality to the AP than the original nodes. From Figure 4.14(a), we see the value of building the RC set. Moreover, while the random grouping over the RC scheme can balance the number of nodes per Wi-Fi Direct group, the Hungarian-based algorithm maximizes the probability of successful data delivery (20% or more compared to the legacy Wi-Fi) by also taking into account the quality of each wireless link. The same improvement can be observed in terms of the network throughput (not reported here for space reasons). Figure 4.14(b) shows the average PDR when varying the T share parameter, while keeping constant the number of nodes (equal to 14) and λ . Clearly, the performance of all schemes increase with higher values of T share, since the Wi-Fi nodes have more opportunities to access the channel. For $T_{share} \leq 33\%$, packet drops occur also for the LTE OFF case due to buffer overflow at the AP. Figure 4.14(b) confirms that the Hungarian Algorithm approach maximizes the performance, with an improvement of 31% PDR compared to the legacy Wi-Fi for $T_{share} = 75\%$. The same conclusions can be derived from Figure 4.14(c), where we show the average PDR as a function of λ , with $N = 10$ and $T_{share} = 50\%$.

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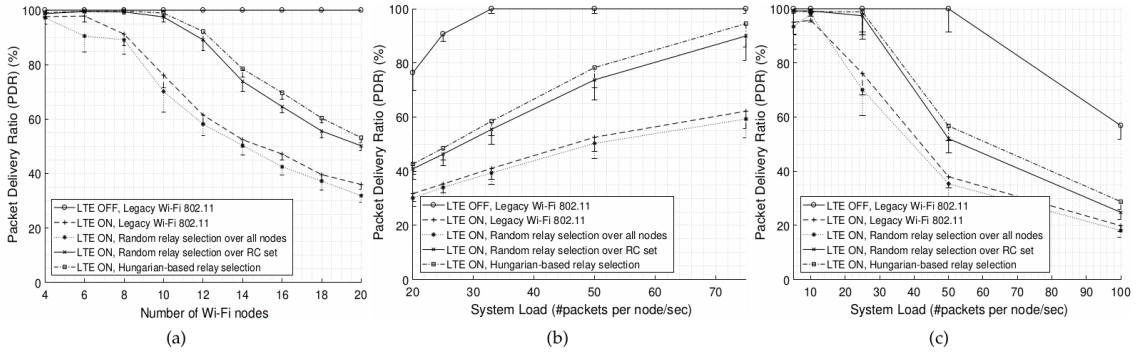


Figure 4.14: The PDR is shown as a function of the number of Wi-Fi nodes (a), the T_{share} parameter (b), and the λ parameter (c)

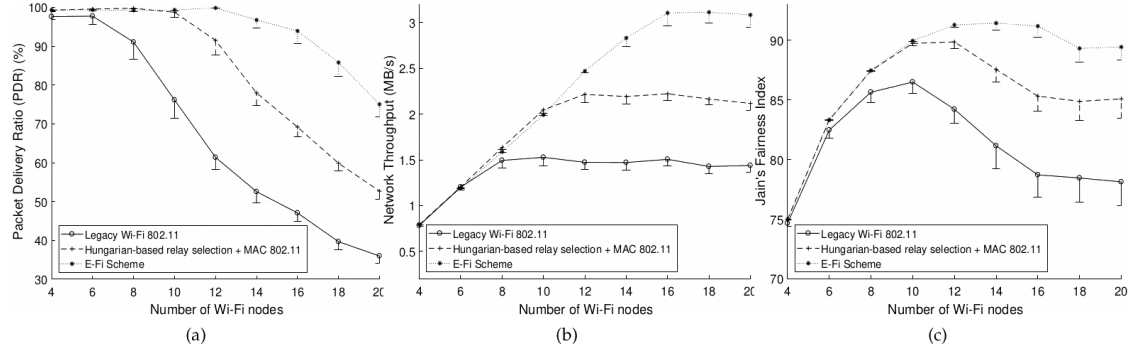


Figure 4.15: The PDR (a), throughput (b) and Jain's fairness index (c) are shown for E-Fi and other competing schemes.

4.3.6.6 ABS Resource Allocation Network Analysis

Figures 4.15(a), 4.15(b) and 4.15(c) depict the system performance when the packet scheduling policy is taken into account. As before, λ is set to 25 pkt/sec, T_{share} equal to 50%, with a variable number of Wi-Fi nodes in the network. Again, we compare the performance of three different schemes:

- The Legacy Wi-Fi 802.11, i.e. the current practical systems deployed today.
- The Hungarian-based relay selection mechanism, where the legacy 802.11 DCF is used at the MAC layer.

- The full E-Fi framework, where both the Hungarian-relay selection and the ABS allocation algorithm are employed with differentiated contention access.

Figure 4.15(a) shows the average PDR for the three schemes. We see that (i) the ABS allocation algorithm provides a significant improvement to the performance of E-Fi, which now outperforms the legacy Wi-Fi standard by almost 100% percent in highly dense scenarios (i.e. $N=20$); (ii) even in these extreme situations. The PDR of E-Fi gets considerably close to the baseline reference (LTE OFF in Figure 4.15(a)), with only 20% difference in terms of PDR. Hence we argue that the Wi-Fi network can really survive LTE-U using E-Fi, mitigating most of the interference coming from the BS. The same inference can be derived in terms of throughput shown in Figure 4.15(b). Finally, Figure 4.15(c) shows the throughput fairness among the N data flows, computed using the well-known Jains Fairness index. Also in this case, E-Fi provides the best performance because: (i) the Hungarian-relay selection mechanism guarantees average higher link quality for vulnerable clients; (ii) the inter-ABS scheduler allocates channel opportunities in a fair way based on the load factor of each Wi-Fi Direct group (4.6); (iii) the intra-ABS scheduler adjusts the MAC back-off parameters so that the AP and the relay will have proportional channel access during each ABS.

4.3.6.7 Experimental Results

In this Section, we evaluate the performance of E-Fi on a small-case testbed. More specifically, our goal is to demonstrate that, despite the additional overhead introduced by the Wi-Fi Direct and by the multi-hop communication, the E-Fi scheme is able to improve the performance of Wi-Fi nodes under several different network topologies and LTE interference levels. To this aim, we built the testbed depicted in Figure 4.16, composed by four nodes: a Wi-Fi Direct Client (WDC), a Wi-Fi Direct GO (GO), a legacy IEEE 802.11 AP, and a corresponding node (CN), connected to the AP via Ethernet. In the experiments, the WDC is constituted by a Nexus 6 smartphone with the Android 6.0 Operating System (OS), and the GO is a Nexus 5 smartphone with the Android 5.0 OS. The GO acts as relay of the traffic produced by the WDC and sent to the CN via the AP. We deployed an Android application (screen-shots are reported in Figure 4.16) which is installed on both the WDC and GO nodes, and implemented the group formation algorithm described previ-

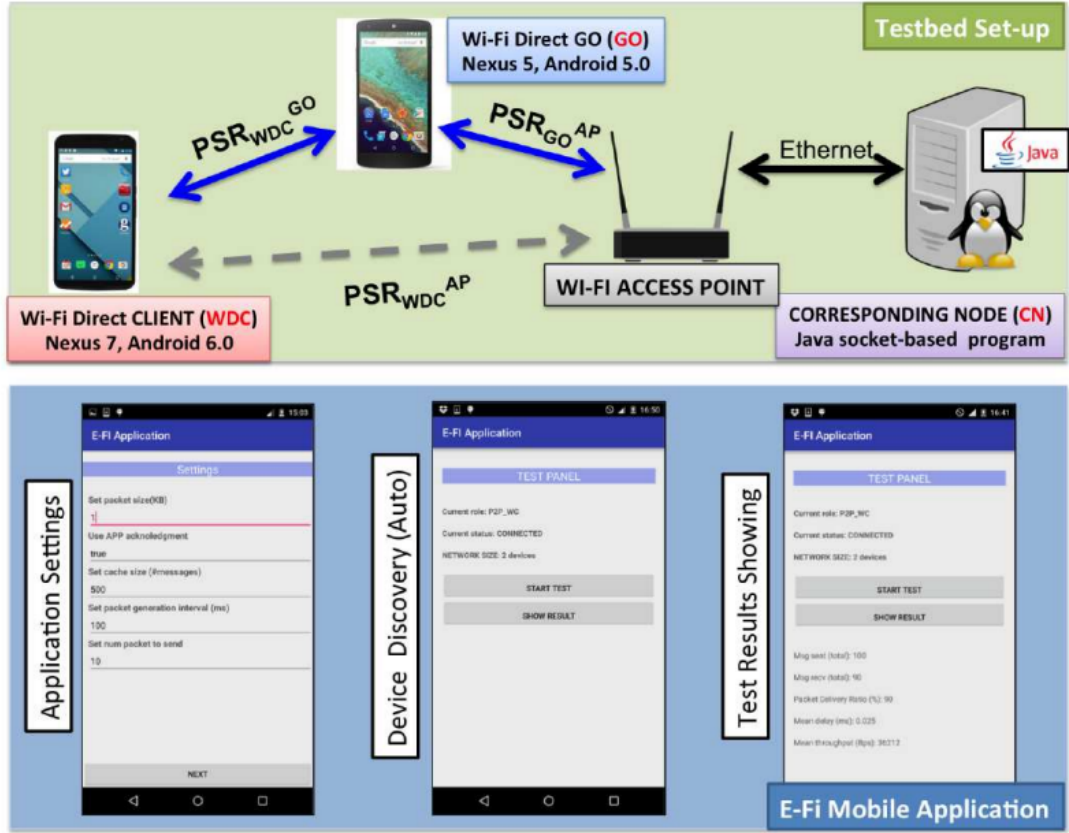


Figure 4.16: The devices composing the testbed and the E-Fi mobile application.

ously and the data forwarding mechanism. On each test, the WDC generates a constant load of κ UDP packets for second; such parameter can be tuned by the user through the application GUI. On the CN, we deployed a simple Java socket-based program, which sends back an application ACK to the WDC for each data packet correctly received. At the end of each test, performance metrics like the network throughput, PDR and delay, were displayed on the GUI of the WDC. We remark that all the network setup procedures, like PSR exchange, device discovery and role selection, are performed in background by the E-Fi mobile application without the need of human intervention. The LTE interference was modeled by varying the packet Success Rate (PSR) on the WDC-AP link (PSR_{WDC}^{AP}), on the WDC-GO link (PSR_{WDC}^{GO}) and on the GO-AP link (PSR_{GO}^{AP}). First, we analyze the overhead caused by the GO relay on the end-to-end communication, and the conditions under which a throughput gain can be achieved.

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To this aim, Figure 4.17(a) compares the throughput of two network configurations (i) a no-relay configuration, where the WDC send the packets directly to the CN, experiencing a loss rate equal to $1 - PSR_{WDC}^{AP}$ on the wireless link, and a (ii) relay-enabled configuration, where the WDC always sens the packets to the CN via the GO, experiencing a loss rate equal to $1 - PSR_{WDC}^{GO}$ on the first link, and $1 - PSR_{GO}^{AP}$ on the second link. The no-relay scheme constitutes the state-of-the-art situation when LTE and Wi-Fi coexist in the same spectrum. We set κ equal to 300 packets/seconds on all tests. In the Figure, we vary the PSR_{WDC}^{GO} parameter (on the x-axis) and we depict curves for different values of PSR_{GO}^{AP} and of PSR_{WDC}^{AP} ; in this latter case, the throughput is an horizontal line since it is not affected by the PSR_{WDC}^{GO} parameter, but we decrease the value of PSR_{WDC}^{AP} to 60%, 40% and 20%. The regions where the relay-enabled curves are over the no-relay line correspond to the PSR configurations where the utilization of the GO device effectively increases the performance of Wi-Fi. We can easily notice that under moderate and severe interference conditions (i.e. $PSR_{WDC}^{AP} = 20\%$ and $PSR_{WDC}^{AP} = 40\%$), the relay-enabled scheme outperforms the standard Wi-Fi under several PSR configurations. This is in accordance with the simulation analysis provided previously.

In Figure 4.17(b) we show the throughput gain of the e-Fi scheme, considering $\kappa = 300$ and severe LTE interference conditions ($PSR_{WDC}^{AP} = 20\%$), and by varying the PSR_{WDC}^{GO} parameter (on the x-axis) and the PSR_{GO}^{AP} parameter (on the y-axis). The gain is computed as the throughput increase (in percentage) compared to the no-relay scheme. In our implementation, E-Fi employs the utilization of the GO relay only when the PSR condition in 4.3 is met; otherwise, the WDC will transmit data directly to the CN as in the no-relay scheme (hence achieving a zero gain in these cases).

From Figure 4.17(b) we notice that the throughput gain can exceed the +500% under some configurations, with a mean value of +85%. Similarly, Figure 4.17(c) shows the throughput of E-Fi and no-relay schemes when increasing the κ parameter, i.e. the network traffic injected by the WDC client towards the CN. We consider these parameters: $PSR_{WDC}^{AP} = 20\%$, $PSR_{WDC}^{GO} = 80\%$ and $PSR_{GO}^{AP} = 80\%$ which means that the E-Fi scheme always employs the GO relay, accordingly with Equation 4.3.

We can easily see that the E-Fi scheme greatly outperforms the no-relay configuration, with a throughput gain of around +300% over all the values of κ . We can hence conclude that

E-Fi is able to cope with the overhead of device grouping and multi-hop communication guaranteeing a significant throughput increase compared to the state-of-the-art scenario under severe LTE interference conditions.

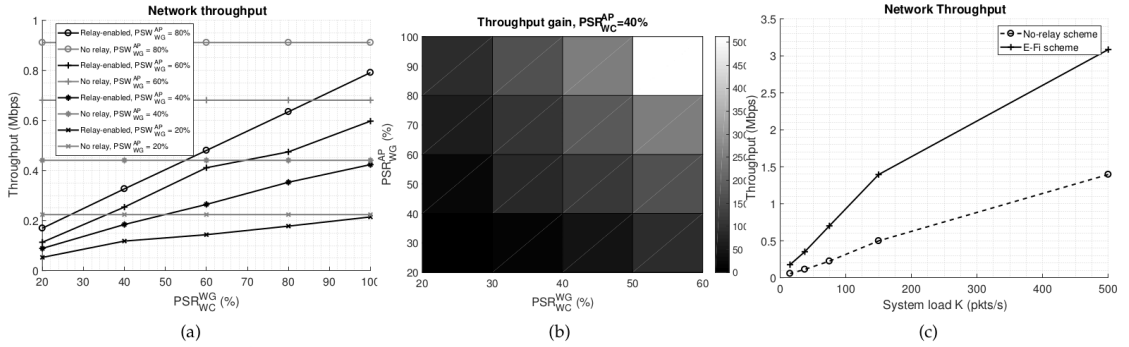


Figure 4.17: Testbed results. The network throughput and E-Fi throughput gain for different configurations of PSR_{WDC}^{AP} and PSR_{WDC}^{GO} are depicted in (a) and (b), respectively. The throughput of E-Fi and no-relay schemes as a function of the traffic intensity (κ parameter) is depicted in (c)

4.4 MATLAB/NS-3 Accurate Coexistence Emulation

The high data rate requirements and density of modern mobile networks have led to a serious interest in exploiting unlicensed bands, especially in the 5GHz spectrum thus facing the currently deployed 802.11 technologies. The challenges associated cannot be underestimated and a surge in publication proposing assessing and defining the problems of LTE/WiFi coexistence appeared. What we propose is an LTE coexistence policy to access the 5GHz band and a step further by realizing a real-time SDR based LTE node implementing said policy.

3GPP Long Term Evolution (LTE) is considered as the de-facto standard for wireless broadband data networks of the future, and a pathway for eventual evolution into 5G networks [86]. The ambitious goals for such wireless networks through design and deployment of LTE networks require accurate simulation tools that provide the standards-compliant implementation. This is the first step towards cost-effective methodical validation and evaluation of ideas that span across the network protocol stack. As shown in previous studies [62] and [15], true PHY layer-compliant operation has a tremendous impact in practical deployment on upper layer protocols. Additionally,

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interference management is a crucial aspect of network deployment given the anticipated densification in 5G networks, for which a simulation environment that captures the details of PHY operation, and a scalable MAC and network-layer is of utmost relevance and importance.

Through our experience while working on the E-Fi concept, and the subsequent evaluation that combined NS-2, Matlab and testbed experimentation, combined with our prior work with Network Simulations, we saw the opportunity to move to more integrated and realistic simulation/emulation setup. A setup that would provide a single environment where it would be possible to run LTE/WiFi coexistence simulation that combines both Network Level and physical layer standard compliant implementations. The availability of Matlab LTE System Toolbox[58] and a full implementation of the LTE Physical layer and NS-3 standard compliant LTE MAC/Network Layer implementations[14] are two enabling solutions for building such a simulation platform that we investigate in the section 4.4.

4.4.1 MATLAB LTE toolbox features

MATLAB provides a highly optimized simulation platform with distributed computing, GPU acceleration and many toolboxes [57]. In particular, the LTE system toolbox [58] enables the generation and manipulation of standards compliant LTE Waveforms, hence allows to simulate/test/validate complex LTE signal configurations. While MATLAB provides detailed and industry-accepted signal generation and channel models, it lacks the support of higher network level protocols that will facilitate inter-node coordination studies.

4.4.2 NS-3 simulation features

NS-3 is a packet-level simulator that enables accurate implementation of LTE upper layers. However, the effects of LTE PHY behavior are not fully captured here since they use a limited spectral resolution of one resource block (RB) in the simulations. Also, the effect of the channel-induced behavior on control channel signals, e.g. Physical Control Format Indicator Channel and Physical downlink Control Channel is heavily abstracted. This does not accurately model the control channel decoding, hence many configuration-related and link failure cases, such as in [28], are overlooked. Although transmit and receive diversity is considered in the implementation, the ex-

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act performance improvement resulting from such PHY techniques is not adequately demonstrated in NS-3 simulations.

4.4.3 Our proposal

In this work, we demonstrate an accurate full-stack LTE simulation environment that unifies implementation and testing of LTE algorithms in PHY, MAC and network layers based on MATLAB LTE system toolbox in combination with NS-3 LTE module. Any innovation in the PHY layer techniques can be put to test in this integrated framework so as to fully understand the entire network behavior. We believe that new research thrusts such as interference alignment, full-duplex and CoMP techniques are some examples that can be tested in our framework in the future.

4.4.3.1 LTE Signal Generation in NS-3

We take advantage of the modular design of NS-3 LTE implementation [14] in which PHY details are encapsulated in 2 main classes: `LteEnbPhy`, `LteUePhy`, which handle eNodeB (eNB) and User Equipment (UE) specific frame construction details, respectively.

`LteEnbPhy` handles the start and end of both frames and subframes via the methods: `StartFrame`, `StartSubframe`, `EndFrame` and `EndSubframe`. The messages to be transmitted at each subframe (and the MIB at the beginning of the frame) will all be queued in a vector of `LteControlMessage` elements. The content of this vector is the abstraction mapping of the actual transport channels into their physical channels then into the resource block grid.

`LteUePhy` handles transmissions by first specifying the uplink spectrum resources according to the allocation map received from the eNB, via `SetSubChannelsForTransmission`, which is initiated by `SubframeIndication`. Similar to `LteUePhy` queues of `LteControlMessage`, elements are generated here to represent the resulting subframes.

For both the cases of eNB and UE, transmission proceeds by a call to `StartTxDataFrame` that handles data frames; `StartTxCtrlFrame` that handles control frames; or `StartTxUISrsFrame` that handles uplink Sounding Reference Signal generation. In each case, a `LteSpectrumSignalParameters` data structure is generated with the following information:

- A `PacketBurst` that contains the payload of upper layer protocols in NS-3 Packet Format.

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- A SpectrumValue that represents the power spectral density of the signal to be transmitted (and it is the basis of all interference, error and channel characteristics that will affect this signal [14]).
- A vector of LteControlMessage elements
- The Cell ID
- A PSS boolean value to indicate the transmission of primary synchronization signal.

The last step would be to call the channel model and provide LteSpectrumSignalParameters as input.

4.4.3.2 Integration Approach

We describe the system design and implementation using Figure 4.18. We make as few modifications as possible to the main LTE implementation code in NS-3. For that reason we have created a new Channel model called MatlabChannelModel, which is an NS-3 abstraction that intercepts the LteSpectrumSignalParameters containing all the necessary information to proceed with MATLAB based signal processing and frame construction.

We then convert LteControlMessage elements, into their MATLAB counterparts calling LTE system toolbox functions. After this, since NS-3 makes a call to the channel's StartTx functions in each subframe of 1ms, MATLAB will be called every 1ms to generate an accurate representation of a subframe based on the content of LteSpectrumSignalParameters (see Fig. 4.19).

For data transmission, NS-3 encapsulates data from all upper layers into a PacketBurst data structure, which contains a description of the packet data structure. The packet type supports data serialization, which allows us to get a bitstream representing the payload to append to the respective transport channel in MATLAB while constructing the subframe resource block grid.

Interfacing with MATLAB is enabled through the Engine API that enables third party applications to interact with its computational engine and simulation capabilities directly. The following are relevant parts of this API:

- engOpen(): Start MATLAB engine session.
- engEvalString(): Evaluate expression in string.

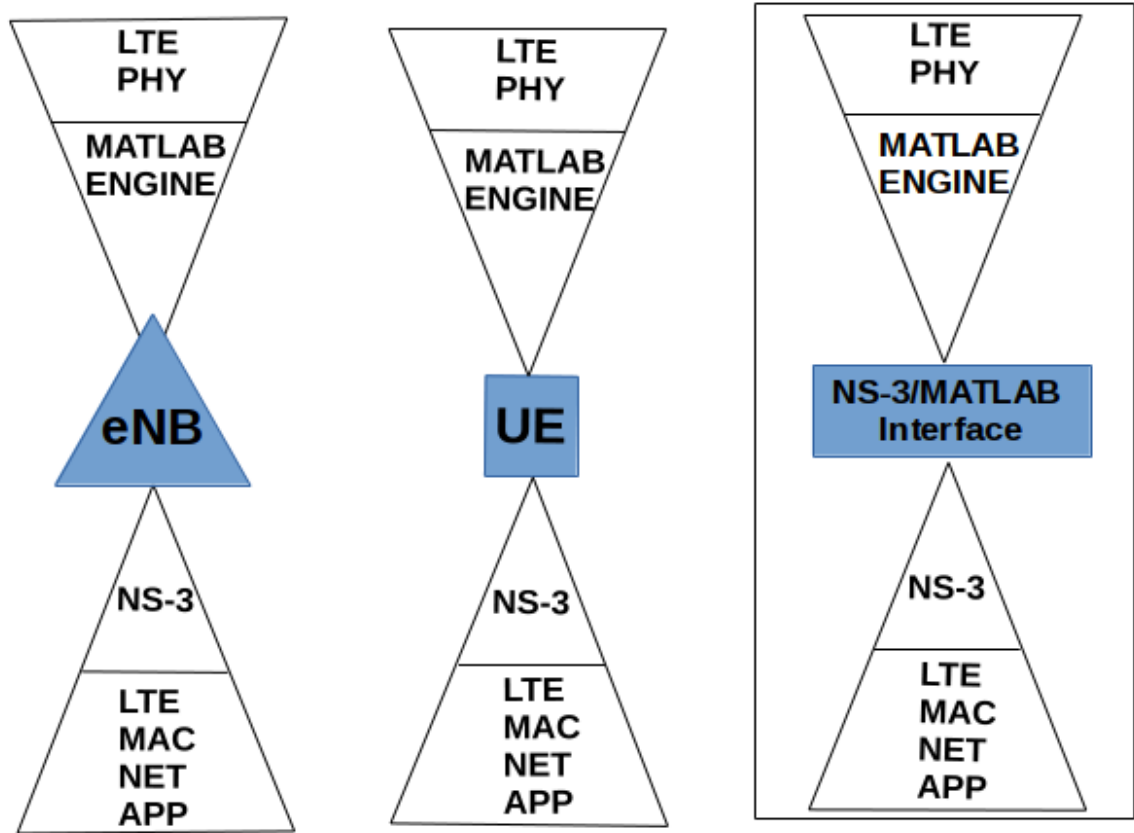


Figure 4.18: Proposed joint MATLAB-NS3 system model.

- `engGetVariable()`: Copy variable from MATLAB engine workspace.
- `engPutVariable()`: Put variable into MATLAB engine workspace.

4.5 Conclusion

We proposed E-Fi, which allows Wi-Fi devices to survive uncoordinated LTE transmissions through the grouping of nodes into relays, separating Uplink/Downlink traffic durations and modifications to the backoff based on PSR. Our design is motivated through studies conducted with standards-compliant LTE and WLAN physical layer wave-forms. We showed for the first time that Wi-Fi can intelligently adapt its operation to handle high PSR and lack of channel access opportunities through the use of ABS frames.

Through a mix of packet-level simulation using standards-compliant physical layer, as well as testbed experiments, we show that E-Fi's improvements over classical Wi-Fi range from 26-

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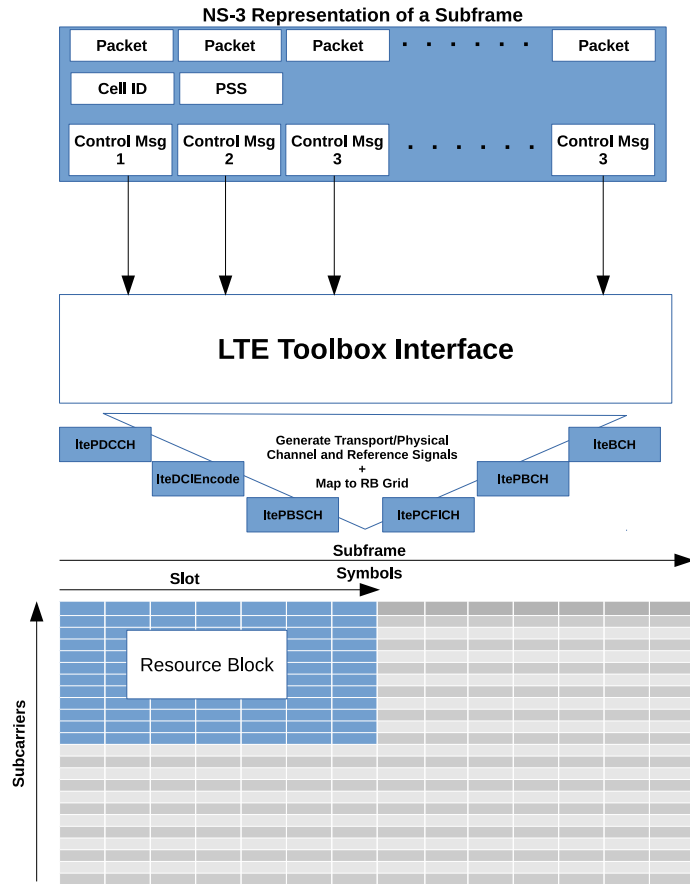


Figure 4.19: NS-3 to MATLAB Subframe conversion/generation.

50% for throughput and 10% for PSR under severe interference from LTE. Our work demonstrates that it is indeed possible to coexist without assumptions of direct feedback between these two very different access technologies in the ISM band.

We also demonstrated a system design for a full LTE stack simulation environment that allows for accurate evaluation of PHY and channel effects in a network wide context. Scenarios such as PHY layer full-duplex, coexistence and interference issues can be studied in simulation with a high level of fidelity in realistic settings.

Chapter 5

Conclusion

Heterogeneous Wireless Networks are a current reality. They are a natural evolution lead by active researches and development and continuous rising demands for higher and higher capacities, lower latencies and innovative new applications. As they increase in complexity and growth, they will eventually continue to be the networks of the future in new and evolved topologies and architectures.

Our proposed simulation framework in Chapter 3, provides a modern versatile environment to experiment with new advances in cognitive networks techniques, spectrum sensing and dynamic spectrum access and heterogeneous networks coexistence. It relies on a modern advanced simulation library NS-3, that provides a rich platform for the development of simulation models at tunable levels of Physical Layer details and provides an actively developed set of standard-compliant libraries that integrates seamlessly with our simulation framework. This seamless integration allows creative ways to combine existing upper layer protocols (TCP flavors, Applications, Routing Protocols ... etc) and study their behavior and possible optimizations or develop new protocols tailored for new needs.

In Chapter 4 we extended our work to tackle the specific problem of LTE/WiFi coexistence and proposed set of solutions that range from Simulation/Emulation, experimental testbed to a novel optimization algorithm for the coexistence problem. In Section 4.2 we built a testbed based on off-the-shelf equipment and widely used SDR platforms combined with open-source libraries, to provide and experimental setup for our current and future work on the coexistence problem and for

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the validation of coexistence assumptions related to the behavior of LTE in unlicensed bands that were necessary to propose the solution in section 4.3.

In Section 4.3 E-Fi was proposed, a new coexistence technique that relies on the ability of Wi-Fi devices to survive uncoordinated LTE transmissions by evading harmful interference. This was achieved through nodes clustering, where some nodes are defined to behave as relays, then E-FI will separate and schedule Uplink/Downlink traffic durations plus modifications to the WiFi-s backoff process based on Packet Success Rate of nodes. As we mentioned before, our experimental testbed helped motivate this design which was subsequently tested through a combination of NS2/NS3 and Matlab simulation.

Inspired by this work, we defined the problem of how to achieve accurate simulations that combine Network Level with Physical Layer simulations in an integrated environment, mainly motivated by LTE/WiFi coexistence problem. Thus, we moved on to propose a NS-3/Matlab integrated simulation environment in Section 4.4 that could eventually aid in future work and provide an advanced level of realism to our studies and also to the research community.

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