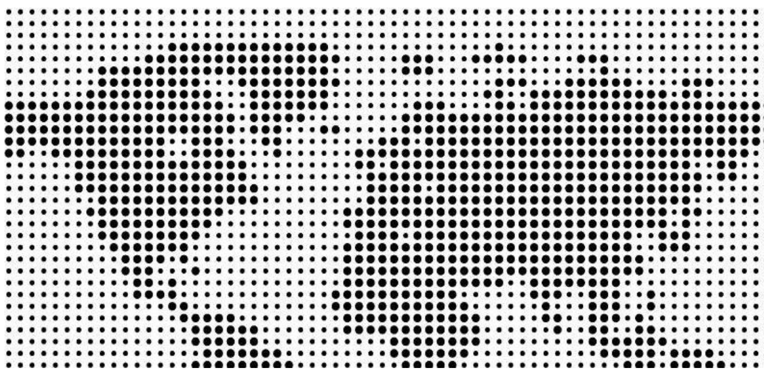
A Comparison of LTE Advanced HetNets and Wi-Fi



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Executive Summary

With the proliferation of smart phones and plethora of connected devices, wireless operators face increasing demand for mobile broadband services. Long-Term Evolution (LTE) allows operators to use new and wider spectrum and complements existing 3G networks to handle even more mobile traffic. However, radio link improvement is fast approaching the theoretical limit and the spectrum available to operators is often limited and expensive. The next performance and capacity leap will come from network topology evolution by using a mix of macro cells and small cells – also referred to as a Heterogeneous Network (HetNet) – effectively bringing the network closer to the user.

The HetNet techniques introduced in LTE Advanced, namely enhanced inter-cell resource and interference coordination (eICIC) in the network, and advanced terminal receivers with interference cancellation (IC), enable operators to deploy low power small cells in addition to macro cells in the *same* channel. By leveraging these innovative techniques, operators can maximize the spectrum efficiency per unit area (bps/Hz/km^2) and provide higher network capacity and enhanced user experience.

To complement their managed Wide Area Networks (WAN), operators can also overlay Wi-Fi networks in unlicensed spectrum. Since most smart phones and tablets today have built-in Wi-Fi access, mobile operators can offload data from macro networks to Wi-Fi networks at residence, in office buildings or at public hotspots. However, for public hotspots operators need to either build and operate their own Wi-Fi networks, or reach an agreement with other Wi-Fi network operators.

For an LTE operator that needs to significantly increase network capacity, there are two complementary options of offloading macro user traffic – Using LTE Advanced HetNets with small cells (pico cells) in the *same* channel as macro cells and using 802.11n Wi-Fi access points (APs) in unlicensed spectrum. This paper compares the system performance of complementing LTE macro cells with low power nodes (*co-channel* pico cells and Wi-Fi APs in unlicensed spectrum) using different network layouts, different carrier frequencies for LTE and Wi-Fi, and different types of user distributions within the network. The results indicate that with the same number of low-power nodes, pico cells offer a superior performance than Wi-Fi APs due to expanded coverage of LTE Advanced pico cells. Wi-Fi is effective in improving user experience

when a significant portion of users are located in the vicinity of hotspots and can be offloaded to Wi-Fi APs.

[1] Introduction

Operators facing capacity challenges in limited spectrum can follow the conventional route of macro cell splitting by inserting more macro cells to their existing networks. However, this can be challenging and economically unattractive due to high CAPEX and OPEX. Low power cells, such as pico cells, can be more attractive because of their small cell site footprint, ease of deployment, and low equipment and operating costs. Wi-Fi can also be used to offload traffic as Wi-Fi is becoming ubiquitous in new devices. Operators can use a combination of pico cells and Wi-Fi APs to offload traffic. Both options can address network capacity issues; however, there are important differences in performance with the usage of pico cells and Wi-Fi APs that we wish to highlight.

In this paper we compare these two options of HetNets in the context of an LTE network and analyze the performance of a heterogeneous network layout consisting of high power macro cells and low power small cells comprising of either *co-channel* pico cells or Wi-Fi APs in unlicensed spectrum. User experience is encapsulated in the form of user throughput CDF and is compared for the two options with uniform and non-uniform ("hotspot") user distributions within the network. Additionally, we provide qualitative considerations when comparing these two options.

[2] Small Cells in LTE Advanced HetNets

Consider an LTE Advanced network consisting of both high power macro cells and low power pico cells or Wi-Fi APs. The macro cells are placed in a uniform hexagonal grid in this simulation model and the low power cells are randomly distributed within the macro coverage. We consider the following two scenarios of user distribution:

- **Uniform:** User Equipments (UEs) are randomly and uniformly distributed in the geographic coverage area of macro cells.
- **Hotspot:** A fraction of the total UEs are randomly placed within 40 meters around the low power cell and the remaining UEs are randomly and uniformly distributed within the macro cells.

2.1 Wi-Fi Option

Simulation parameters for Wi-Fi APs based on the 802.11n standard [3] are shown in Table 2. An IEEE Channel model D is chosen for the simulations as it has been extensively validated in the Wi-Fi literature [4] for typical enterprise and large home environments, with indoor wall mounted APs. Channel model D may also extend reasonably well for hotspots, assuming APs have low height. However, the delay spread of Channel Model D is too small (less than 1 µs) to be applicable for typical outdoor hotspots and in that sense, the corresponding Wi-Fi analysis should be considered as somewhat optimistic. There is no resource partitioning or interference between the macro cell and Wi-Fi APs as in LTE and Wi-Fi networks operate on disjoint frequency bands. The Wi-Fi frequency band of 5.5 GHz is considered, where there are 24 non-overlapping Wi-Fi channels available. The interference from neighboring Wi-Fi APs is not modeled by assuming there is some Wi-Fi network planning or intelligent channel selection. No load balancing across macro and Wi-Fi APs (or across Wi-Fi APs), or power control across overlapping Wi-Fi APs is assumed.

2.1.1 Association Method

In this simulation scenario, each UE stays in one location and is associated with either a macro cell or a Wi-Fi AP. A UE is offloaded from WAN and associated with a Wi-Fi AP whenever it can be served by the Wi-Fi AP with at least the lowest modulation and coding scheme (MCS) of Wi-Fi (6.5 Mbps for 802.11n)[1]. Once the UE joins the Wi-Fi network, it becomes a Wi-Fi client. Since the client has lower power (18 dBm) than the AP (21 dBm/antenna), the coverage range of Wi-Fi is typically limited by the uplink.

2.2 LTE Pico Option

In this simulation scenario, the LTE evaluation methodology specified in 3GPP (Table 1) for a co-channel macro/pico HetNet deployment is used. We use advanced receivers at the UE with interference cancellation to complement network based enhanced inter-cell interference coordination (eICIC).

As part of the eICIC scheme, within the coverage of each macro cell, some subframes are exclusively used by pico cells to serve UEs in each pico cell's extended range, while other subframes are used by both macro cells and pico cells. In the subframes exclusively used by pico cells, the macro cell does not transmit any traffic but still

[1] 1 Mbps 802.11b rate was not considered as the minimum rate for association because our simulations showed that in the absence of proper load balancing and admission control algorithms at AP, and AP selection algorithm at the client, 1 Mbps clients take up significant medium time and reduce offload performance of Wi-Fi users with a higher MCS. This leads to overall degradation of network performance.

transmits the common signals (sync, broadcast and reference) and the UEs cancel this interference emanating from the macro cell using their advanced receiver capability. In the subframes used by the macro cell, the embedded pico cells can still schedule UEs in each pico cell's non-extended range.

The partitioning is orchestrated by the macro cell by negotiating with the embedded pico cells and the exact partitioning ratio adapts to the traffic pattern across macro and pico cells in the network.

2.2.1 Association Method

The association rule in the presence of pico cells is based on the maximum downlink received power with a bias adjustable between 0 dB and 18 dB towards pico cells. This implies that the common signal C/I of a UE being served by a weak pico cell can be as low as -18 dB. If no such pico cells are available, the UE will usually be served by the strongest macro cell [1].

[3] Performance Comparison

In this section, we present the results with both large (D3) and small (D1) macro cell inter-site distance (ISD) for uniform and hotspot scenarios [5].

Macro cell ISD is 500 meters (D1 layout) or 1732 meters (D3 layout), representing high and low density macro cell deployment scenarios, respectively. LTE carrier frequency is 700 MHz for D3 scenario and 2.1 GHz for D1 scenario. Hotspot scenario considers 30 total UEs out of which 20 UEs are within the hotspot range while the remaining 10 UEs are uniformly distributed in the macro cell area. The analysis is conducted for all cases with either 1 or 4 small cells (pico cells or Wi-Fi APs) per macro cell.

The performance metrics used are median and cell edge user throughput gains comparing HetNet with macro and low power cell network over macro only network. The median user throughput is used to capture the *typical* user experience, while the cell edge case is defined as the lowest 5^{th} percentile throughput of all users in the area.

3.1 Large Macro Cell (Low Density) Results

Figure 1 shows the simulation results for the large macro cell deployment (D3) and uniform user distribution, with one or four small cells per macro cell.

In this case, Wi-Fi APs provide little or no throughput improvement for median or cell edge users. For example; the gain with four Wi-Fi APs is only 10% mainly due to limited association range of Wi-Fi APs within the large macro cell coverage. The limited range is due to 18 dBm transmit power of typical Wi-Fi clients and minimum MCS of 6.5 Mbps. However, with four pico cells, one can achieve 180% median throughput gain over macro-only network, because LTE Advanced techniques (eICIC and IC) lead to expanded range of pico cells [1].

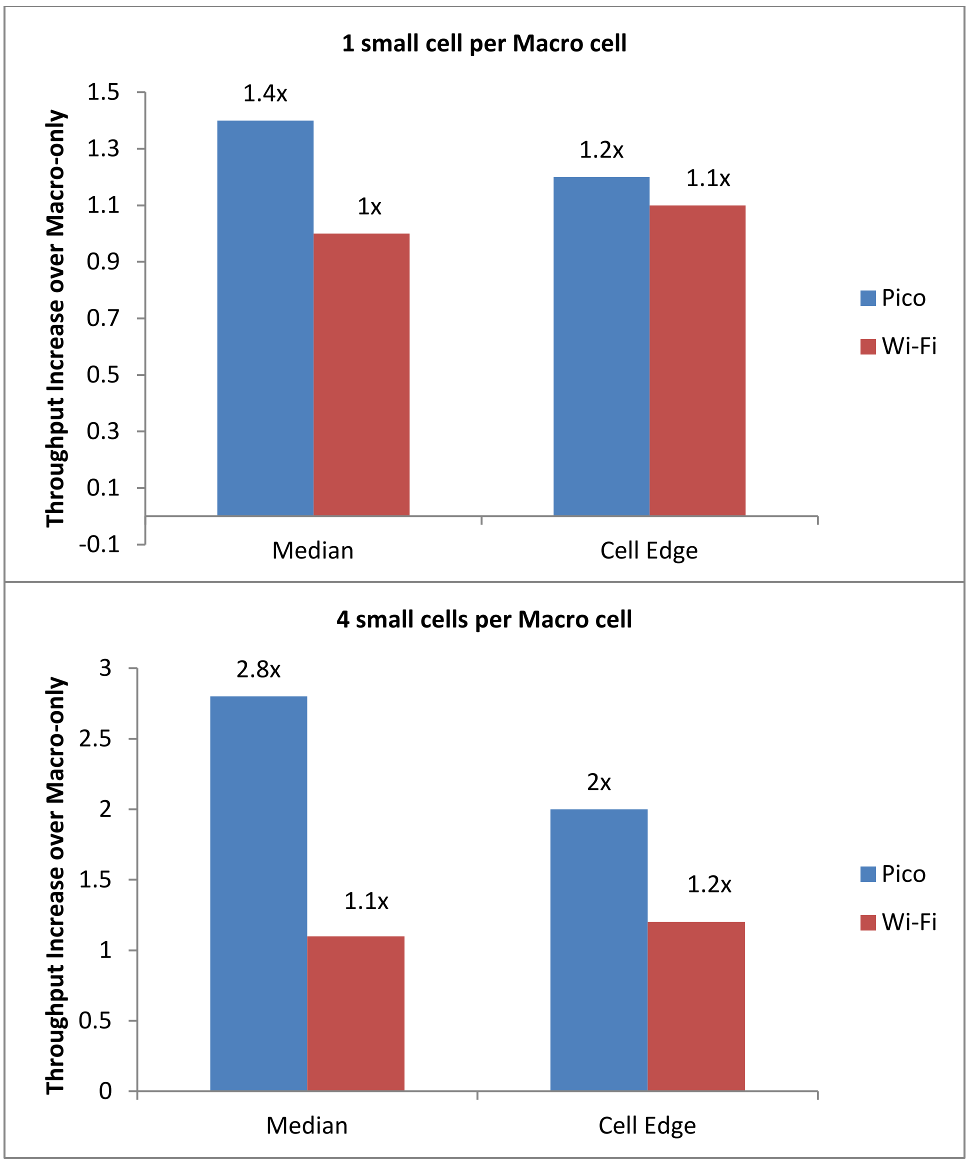

Figure 1: D3 Large Macro Cell Scenario, Uniform Distribution.

Figure 2 presents the simulation results for a hotspot scenario. In the hotspot scenario, many UEs are located in the vicinity of low power cells. A Wi-Fi AP can therefore offload a large number of UEs from the macro cell compared to the uniform scenario.

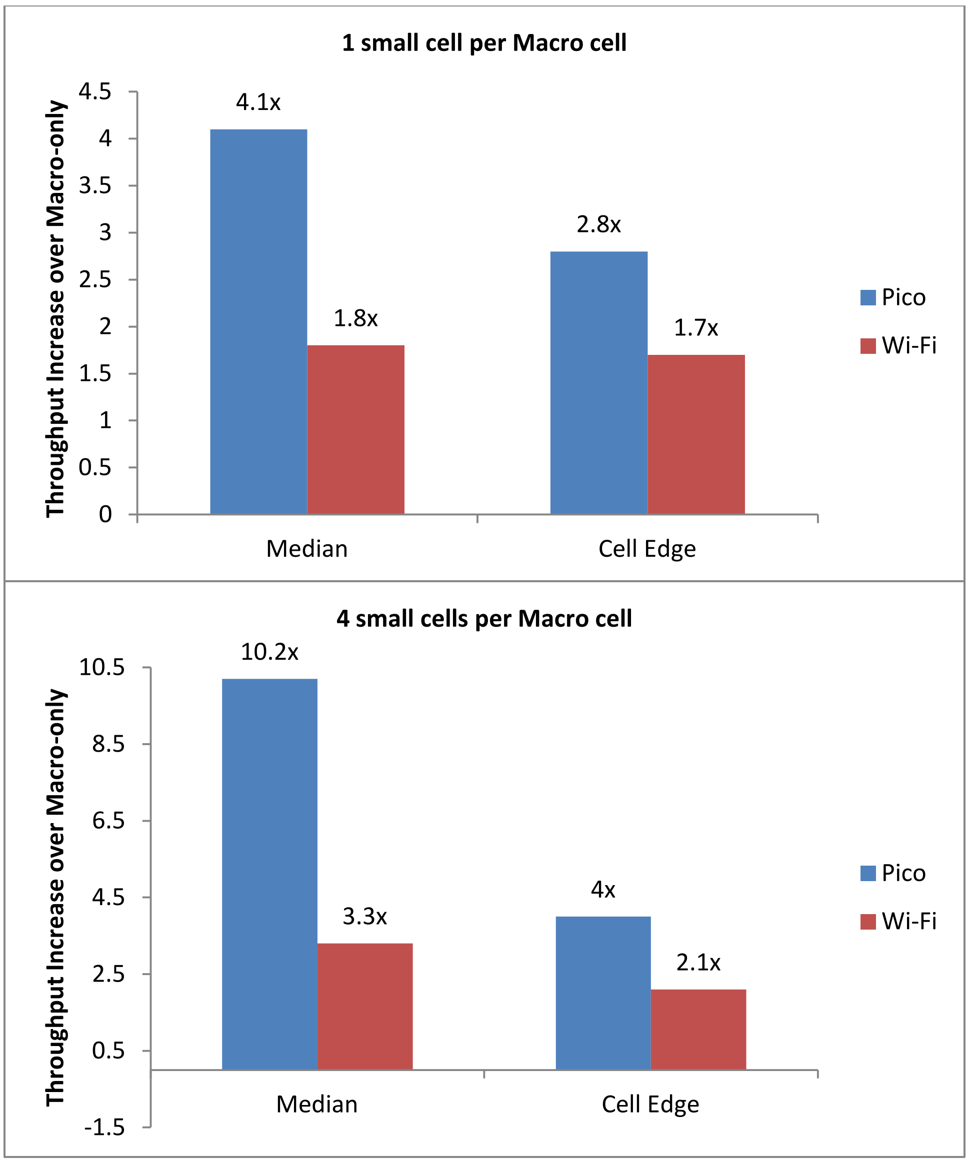

Figure 2: D3 Large Macro Cell Scenario, Hotspot (20/30) Distribution.

In this scenario, Wi-Fi APs can offer significant throughput improvement. For example; four Wi-Fi APs can offer 230% improvement in terms of median user throughput gain. However, LTE Advanced pico cells provide even higher gains in this hotspot scenario. Four pico cells deliver a gain of 920% for median user throughput; this is a significant improvement over what can be realized using Wi-Fi APs. Adaptive resource partitioning between macro and pico cells allows more resource and capacity allocated to pico cells to serve large number of UEs in the hotspots.

3.2 Small Macro Cell (High Density) Results

We now consider a dense macro deployment (D1). Figure 3 shows the results with uniform user distribution. The UE density is now increased because there are more UEs within a unit area compared to large macro cell deployment. As a result, the probability that a UE falls into the serving area of a small cell becomes larger. Therefore four Wi-Fi APs can improve the median user throughput by 70%. Yet the pico cells provide much better offloading performance, with a median user gain of 150% with four pico cells.

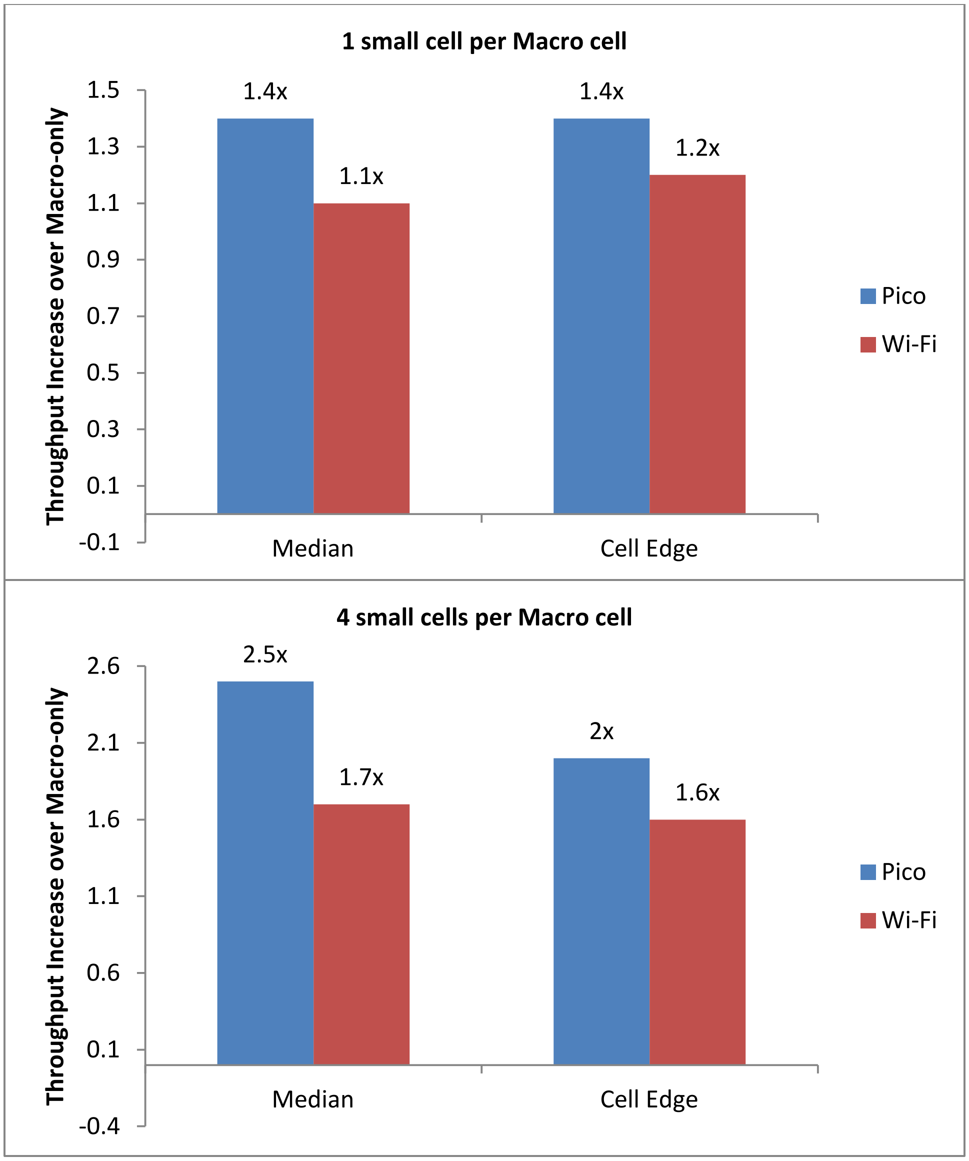

Figure 3: D1 Small Macro Cell Scenario, Uniform Distribution

Figure 4 shows the results with hotspot distribution. For hotspot user distribution scenario, four Wi-Fi APs can offer 250% median throughput gain, while four pico cells can offer 320% gain.

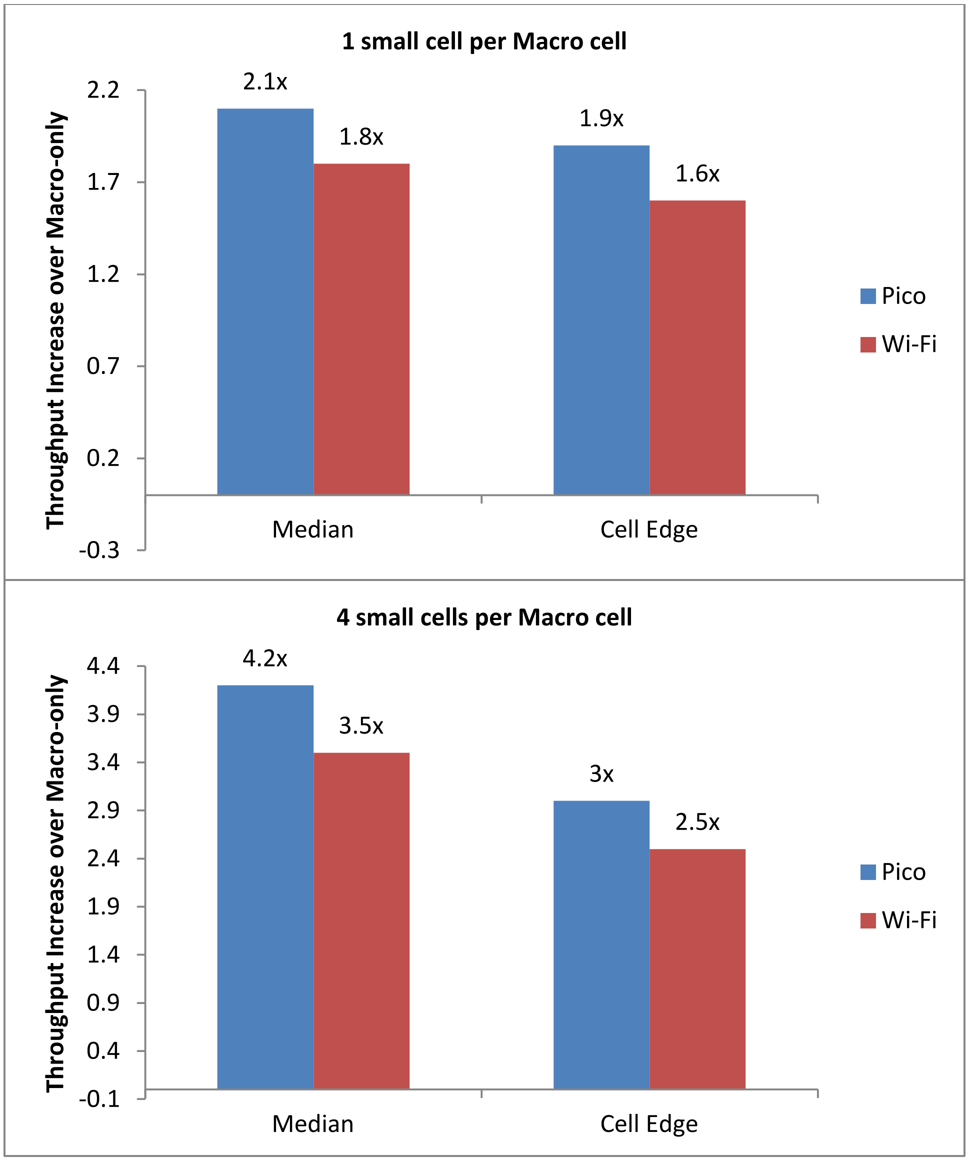

Figure 4: D1 Small Macro Cell Scenario, Hotspot (20/30) Distribution

Based on the above results, it is seen that with the usage of eICIC and IC techniques in LTE Advanced HetNets, co-channel macro plus pico cells consistently outperform Wi-Fi APs deployment. The performance difference is more pronounced in suburban scenarios with relative low density of small cells. For hotspot distribution, four pico cells deliver 10 times median user rate over a macro-only deployment, and perform 200% better than four Wi-Fi APs in the suburban scenario. Range expansion of pico serving areas and adaptive resource partitioning allows pico cells to offload macro traffic far more effectively than Wi-Fi APs that have limited range.

On the other hand, in dense urban scenarios, user concentrations may be predicted and small cells (pico cells and Wi-Fi APs) can be deployed at hotspots such as shopping malls and airports to greatly improve the overall user experience. In a hotspot scenario shown in Figure 4, pico cells still perform slightly better than Wi-Fi APs, however the relative performance gap between pico cells and Wi-Fi APs for hotspot distribution reduces from 200% to 20% for suburban to dense urban scenarios respectively. With a uniform user distribution, the large association range of pico cells prevails and the performance is better than with Wi-Fi APs for both one and four small cell cases. For example, four pico cells perform 47% better than four Wi-Fi APs in terms of median user rate in this scenario.

[4] Other Technical Considerations

In addition to the above quantitative performance, we now discuss other deployment considerations of pico cells and Wi-Fi APs. In addition to adding system capacity operators also need to consider the impacts of mobility, Quality of Service (QoS), security, and Self Organizing Network (SON) capabilities, especially when deploying small cells such as pico cells.

4.1 Mobility

3GPP supports a close integration of macro and pico cells as part of LTE HetNets, with well defined handover procedures. Advanced UEs can detect, measure, report and handover to small cells when signaled to do so, even when the pico signal strength is much weaker than macro signal. In addition, pico cell range expansion and TDM resource partitioning allows UEs to sustain good data rates in the expanded footprint of small cells, which improves overall system performance [1].

Handover to Wi-Fi requires inter-RAT (Radio Access Technology) handover, and 3GPP standard considers Wi-Fi as a non-trusted system. Moving data from 3GPP system to Wi-Fi network requires a new network entity called the Home Agent that anchors the IP flows. The Home Agent along with a Dual-Stack Mobile IP (DSMIP) implementation on the UE can allow for a smoother transition between Wi-Fi and 3GPP network [2].

Most Wi-Fi networks are not well planned, which may lead to inconsistent and inadequate system coverage and capacity. Wi-Fi network operates in unlicensed spectrum and an operator deployed Wi-Fi network is susceptible to interference from other Wi-Fi devices that can further affect range, capacity and mobility performance. The fact that WAN network is not aware of the current radio characteristics of Wi-Fi APs makes the handover between WAN and Wi-Fi more challenging than pico cells. Current solutions for Wi-Fi/cellular selection offer simple ways to offload to Wi-Fi but lack the ability to perform robust handovers to Wi-Fi to satisfy mobility requirements for real-time services, especially in outdoor scenarios. Mobility is also limited in many Wi-Fi deployments as most devices search for a new AP only when the signal from their current AP becomes too weak. Therefore Wi-Fi does not guarantee connectivity to the strongest AP, thereby limiting the potential capacity improvements. Improvements to address mobility issues for Wi-Fi are currently under consideration, which should start becoming available to operators in the near future [2].

4.2 Quality of Service

QoS requirements need to be addressed when considering data offload options. LTE pico cells support QoS as an integrated part of HetNets. Coordination between macro and pico cells facilitates smooth and transparent flow of QoS sensitive traffic flows regardless of whether UEs are served by macro or pico cells. Advanced techniques like range expansion and resource partitioning enable more equitable distribution of airlink resources in the system and help address UE QoS requirements.

Wi-Fi provides four QoS classes (Best Effort, Video, Voice, and Background) with 802.11e. However, Wi-Fi operates in unlicensed spectrum and it is difficult to predict interference and traffic load due to non-operator deployed APs. Hence, Wi-Fi APs are better suited for best effort applications that do not require QoS. Select IP traffic for non-QoS sensitive traffic can be offloaded to Wi-Fi APs when available.

4.3 Security

Security protocols are the same between macro cells and pico cells in the 3GPP network, therefore there are no issues for small cell pico deployments.

When data is offloaded from a macro cell to Wi-Fi AP, user authentication (password or accepting terms) is usually required in public Wi-Fi networks at airports and hotels, etc. It is not convenient for operators to configure each device with these credentials, while manual entry is not desirable in terms of user experience. Operators can configure some methods on the APs and devices such as pre-configuring the operator’s Wi-Fi SSID in the devices.

There is also standardization work done in Wi-Fi to enable EAP-AKA type automatic authentication, which allows 3GPP credentials (SIM) to authenticate the user over Wi-

Fi. This method allows seamless authentication similar to 3GPP, however it will require all of the Wi-Fi providers to adhere to a common standard.

4.4 Self Organizing Network

To support a smooth unplanned deployment of pico nodes, 3GPP LTE has defined SON features that include Automatic Neighbor Relations (ANR), Mobility Load Balancing (MLB), and Mobility Robustness Optimization (MRO). Specifically, ANR helps automatic discovery of new neighbor eNodeBs via UE assistance. MLB allows tuning the handover thresholds between macro and pico cells based on cell loading to balance the load between macro and pico cells. MRO monitors failed handovers to fine tune mobility parameters such as handover hysteresis and trigger-time. These SON features enable optimal mobility and network load balancing for LTE Advanced HetNets.

These features are currently not available between 3GPP access technologies and Wi-Fi; however they are fully supported and available between 3GPP LTE macro cells and pico cells.

[5] Conclusion

Pico cells and Wi-Fi APs are complementary options available to operators when they consider expanding their data capacity. Based on the analysis we have conducted, it is seen that for the same number of small cells in a LTE macro-cell deployment, *co-channel* pico cells offer a significantly better user experience and system capacity improvement than Wi-Fi APs. In addition, LTE pico cells also have better support for mobility/handoff, QoS, Security, and SON.

LTE Advanced HetNet techniques, including eICIC with adaptive resource partitioning, pico cell range expansion, and interference cancellation UE receiver, enable more fair and equitable distribution of resources across the network, and balance the load evenly, leading to significant improvement in typical and cell edge user experience and normalized network spectral efficiency (bps/Hz/km^2). In addition, pico cell based HetNets preserve the key operator requirements of QoS, mobility and security, while SON techniques defined within 3GPP enable a robust and easier unplanned deployment of pico cells.

Wi-Fi uses unlicensed spectrum and *complements* pico cell data offloading in certain scenarios. From the analysis conducted, it is seen that Wi-Fi provides a gain in user throughput when a significant portion of UEs can be offloaded from macro cells to Wi-Fi APs, e.g. for the hotspot scenarios and small macro cell size with high number of users in their vicinity.

[6] System Model and Simulation Setup

The following tables list our important simulation parameter assumptions.

Network Layout	D1 (ISD = 500 m) D3 (ISD = 1732 m)	
#. Macro Cells	57 (19-site wrap-around)	
Antenna configuration	2Tx/2Rx	
Antenna Gain	Macro	14 dBi
	Pico	5 dBi
Carrier Frequency	D1@2.1GHz D3@700MHz	
Shadowing Model	Lognormal Stdev = 10 dB for pico-UE link; 8 dB for macro-UE link	
Penetration Loss	Fixed 20 dB	
Bandwidth	10 MHz	
Traffic Model	Downlink Full Buffer	
#. UEs/Macro Cell	30 (Total: 1710 UEs)	
Scheduler	Proportional Fair	
Macro Tx Power	46 dBm	
Pico Tx Power	30 dBm	
UE Tx Power	23 dBm	
Pico Density per Macro	Fixed: 0/1/4	

Table 1: LTE Advanced System Setup

Carrier Frequency	5.5GHz	
Antenna configuration	AP	2Tx/2Rx
	Client	1Tx/1Rx
Antenna Gain	3 dBi	
Shadowing Model	Lognormal Stdev = 10 dB for Wi-Fi AP-UE link;	
Penetration Loss	Fixed 20 dB	
Bandwidth	20 MHz	
Traffic Model	Downlink Full Buffer + 12.5% Uplink	
Scheduler	Round-Robin	
AP Tx Power	24 dBm	
Client Tx Power	18 dBm	

Maximum TxOP	3 ms
Packet Size	1500 Bytes
RTS/CTS	None

Table 2: Wi-Fi System Setup

[7] Glossary

3GPP	Third-Generation Partnership Project
ANR	Automatic Neighbor Relations
AP	Access Point
eICIC	enhanced Inter-Cell Interference Coordination
HetNet	Heterogeneous Network
ISD	Inter-Site Distance
LTE	Long Term Evolution
MLB	Mobility Load Balancing
MRO	Mobility Robustness Optimization
QoS	Quality of Service
SON	Self Organizing Network
UE	User Equipment
WAN	Wide Area Network

[8] References

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