On the Comparison of Performance, Capacity and Economics of Terrestrial Base Station and High Altitude Platform Based Deployment of 4G

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Abstract: OFDM/OFDMA based physical layer, wide channel bandwidths are the features common to all potential candidate 4G technologies in order to achieve unprecedented high data rates and better QoS. But these very features of 4G necessitate extraordinary small cell size in 4G Wireless Cellular Networks (WCN) to meet the link budgets. This makes an efficient and cost effective ubiquitous deployment solution for 4G WCNs a big challenge. This paper investigates two different deployment solutions for 4G WCNs and presents a comparison between them in terms of performance, capacity and deployment cost factors in relative terms. The first solution is conventional Terrestrial base stations based WCN with reduced cell size (TWCN) and second solution is 4G WCNs deployment via High Altitude Platform i.e. HWCN. WiMAX is taken as bench mark in this study as it is most well known standard that has all the aforementioned characterizing features of 4G technologies. The performance of HWCN and TWCN is evaluated through extensive system level simulations that model realistic details like link level performance, dynamic interference, and shadowing and propagation characteristics of the two systems. Effects of spectrum reuse factor, Adaptive Coding and Modulation (ACM) and user traffic type on the performance of two solutions are investigated and compared in detail. Finally a relationship between the relative deployment costs of the two systems is developed and used to assess the deployment costs of the two systems normalized over the capacity they offer in order to analyze their economic feasibility relative to each other.

Categories & Subject Descriptors C.2.1 [**Network Architecture and Design**]: Wireless Communications.C.1.2 [**Other Architecture Style**]: Cellular Architectures

General Terms: Performance, Design, Economics

Keywords: Comparison, Performance, Capacity, HAP, Terrestrial, 4G

1. INTRODUCTION

All the major candidate technologies for 4G or next generation of wireless networks namely Long Term Evolution (LTE), Ultra Mobile Broad Band (UMB) and 802.16m i.e. WiMAX II have some basic features in common [1] i.e. All of them are being built on OFDM/OFDMA based physical layer, have wide band channels and allow operation at high carrier frequencies. Where these essential attributes of potential 4G wireless standards promise unprecedented higher data rates and fine QoS granularity to support plethora of newly borne bandwidth hungry applications, at the same time they make cost efficient ubiquitous deployment of 4G WCNs a major challenge. Conventional terrestrial and satellite infrastructure represent two well established deployment solutions that have been dominant in the wireless communication arena for decades. But recent field trials show that regular cell sizes are not suitable for deployment of newly emerging wireless standards with the aforementioned features [2]. This is because high processing complexity of OFDM/OFDMA drains mobile terminal's limited battery power much rapidly. This fact calls for a relatively very smaller cell size in 4G terrestrial WCNs. But a small cell size has an economic constraint as it results in higher overall system cost because larger number of Base Stations (BSs) is required to the cover the same area. Further it also has a technical constraint as it increases the overall interference in the system by decreasing the inter site distance among co-channel cells. A second potential solution to the problem of cost efficient ubiquitous deployment of 4G is an aerial deployment. Here the problem of reducing the path loss calls for a solution with lower platform height so that propagation distance is minimized. This could be possible by deploying WCNs through High Altitude Platforms (HWCN). HAPs are stratospheric platforms similar to satellite in their functionality but deployed at much lower heights ranging between 17 and 30km. Recent advancements in aerodynamics, control systems, avionics and power electronics have made commercial realization of such platforms more feasible then ever [3].Their extremely lower height compared to satellite is the main feature that makes them an attractive potential solution for 4G deployment as the propagation distance can be reduced by a factor of at least (10000/30)=300 to maximum 2000=(37000/17) compared to traditional satellite links. This translates into a 50dB to 60dB gain in link budget compared to conventional satellite based deployment WCN.

HWCN is relatively a new concept and instead of the potential advantages that can be obtained with HAPs based deployment of 4G WCN only a few studies are reported on performance evaluation of HWCN. Studies in [4]-[7] focus on the link level performance only. In [5] link level performance at 2 GHz is evaluated and it is shown that for elevation angles above 40^o, HAP can deliver data with acceptable QoS. In [4]-[7] channel models for HAP at Ka band are discussed. Only a few studies are reported that consider performance aspects of HWCN at system level [8]-[11]. They consider a basic analytical approach and are mostly limited to derivation of SINR in HWCN alone [11] or in case of its coexistence with terrestrial networks [8]-[10]. Further none of these studies consider the pragmatic dynamic features of a real HWCN in their assessment of performance. On the other hand, the Terrestrial Base Station based deployment of Wireless Cellular

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Network (TWCN) has been extensively studied in literature in terms of its performance and capacity aspects for exemplary 4G technology i.e. WiMAX. But the system level performance evaluation of a TWCN for a 4G multi cellular scenario with reduced cell size while considering all real aspects that affect system overall performance –e.g. dynamic interference from two tiers of co-channel cells, link level performance, correlated shadowing and sectorization to name few- is an overlooked issue so far. So, to the best of our knowledge, no such work has been reported so far that evaluates and compares the realistic performance and capacity of the two different deployment solutions i.e. HWCN and TWCN for 4G in order to establish a fair performance and capacity comparison and cost feasibility between them. This provides motivation for this study.

WiMAX is taken as bench mark in this study as it is the most well established technology so far that has all the three characterizing features of potential 4G technologies that make its deployment challenging i.e. WiMAX has OFDM/OFDMA on its PHY layer, wide band channel and allows for high carrier frequencies of operation (5GHz in this study). Thus the results obtained for TWCN and HWCN using WiMAX are generally valid for any future 4G technology that resorts on these features.

The contributions of this paper are three folded. First we evaluate the realistic performance and capacity of HWCN for a wide set of system configurations through extensive simulations that incorporate the all major realistic aspects of HWCN that can affect its performance. This mainly include the link level performance of WiMAX in HAP channel at 5GHz, dynamic interference from two tiers of cells and elevation angle dependent correlated shadowing. Secondly we evaluate the TWCN's performance and capacity for WiMAX deployment under same scenarios as for HWCN. Thirdly, we develop an expression to establish a relationship between the deployment costs of HWCN and TWCN and use it to assess the economic feasibility of the two solutions for the similar coverage and service characteristics relative to each other.

The rest of paper is organized as follows. Section 2 explains HWCN scenario and describes the simulation model for HWCN. In section 3, TWCN model is presented. Section 4 presents simulation results for both HWCN and TWCN and discusses the effect of system configurations on the performance of two systems. In section 5 relative cost analysis is presented. Section 6 compares overall performance and relative deployment cost of the two systems. Finally section 7 summarizes the key conclusions.

2. HWCN SYSTEM MODEL

Multi cellular scenario for WCN deployed via a single HAP is considered in this study for performance evaluation of HWCN. System Level Simulator (SLS) developed for HWCN is explained in the following subsections.

2.1 System Design

An HWCN of 19 cells that constitute two tiers of co-channel cells is modeled in SLS. This ensures that a realistic level of interference in a multi cellular environment is considered in performance and capacity evaluation. SLS for HWCN feeds on the link level performance results of WiMAX at 5GHz in HAP channel reported in a previous study in [12] for a range of elevation angle and SINR. Further, for a realistic evaluation, the SLS models all the important pragmatic features of HWCN that can potentially affect its performance. These features include correlated shadowing and its strong dependency on elevation angle in HAP scenario; appropriate path loss models, realistic antenna footprints, and dynamically updated interference from surrounding cells. Table I shows the SLS parameters used in this study.

Table1. Simulation parameters for HWCN

Height of HAP	20km
No. of Cells	19 (two tiers)
Avg Cell radius	5Km
HAP Antenna BW	19.5, 16.5, 14.5 deg for 1st,2nd & 3nd tier antennas
HAP Antenna Gain	Calculated against B.W
HAP Max Tx power	39dBM
User Antenna Gain	0dB
Shadowing Std	4 to 8dB
Elevation Angle	40^o to 90^o

2.2 Propagation Aspects

In order to estimate the propagation loss in a HAP scenario, free space path loss model is used with slight modification to accommodate the additional losses due to air and moisture molecules. Figure1 (left) shows the RSL in the coverage area of HWCN. Shadowing model inspired by [14, pp29-39] is implemented in SLS. This incorporates elevation angle dependent auto-correlation property of the shadowing. Parabolic antenna model is used and the beam widths and the corresponding tilting angles of antennas in first and second tier of antennas are set such that the average footprint radius 5 km for each cell is achieved.

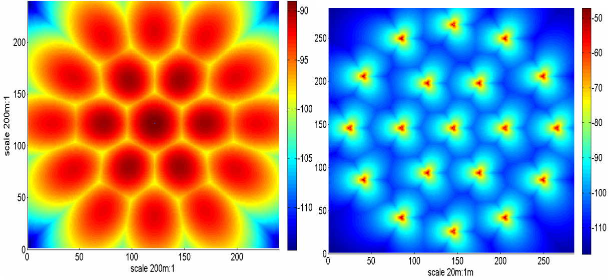

Figure 1: RSL profile in HWCN (Left) and TWCN (Right)

2.3 System Dynamics

Users are registered with respective cells based on maximum received signal level. When a user in a given cell is selected in a round robin fashion, system checks if the number of free slots (WiMAX radio resource units) available with that particular cell are enough to provide the user with requested data rate. If not enough free slots are available, the user is logged as blocked due to *hard blocking* (This happens when system is fully loaded i.e. all the radio resources are already occupied). If enough free slots are available, system then calculates the expected Packet Error Rate (PER) for that particular link condition of the user using the look up tables obtained through link level simulation results. The effective SINR is estimated by averaging the SINR on all the subcarriers to be allocated. If user is not expected to achieve a PER better than a certain threshold even for the most robust ACM scheme, user is considered softly blocked i.e. blocked due to low SINR or bad signal quality; otherwise user is permitted admission into system and starts receiving data using the most efficient possible ACM that allows a PER better than the threshold. The value of this threshold depends on type of application. An arbitrary value of 10% is used in this study. The particular slots required to meet user transmission rate demand are allocated by resource allocation mechanism in operation. In this study, we have implemented a resource allocation scheme that randomly allocates the requested amount of WiMAX radio resource units to the admitted user by specifying the slots and sub carriers for that particular user. (Such random sub-carrier allocation scheme can approximate PUSC on PHY layer without introducing significant error [13]). The admitted user is then logged as *successful user* and the interference caused by this new user is instantaneously added to respective time slots on all the respective subcarriers allocated to other users. Number of users, successfully admitted or softly or hardly blocked is logged until the system becomes fully loaded or stable. The average cell throughput, soft and hard blocking and spectrum utilization on the central cell only is logged to include full interference effect in performance evaluation.

3. TWCN SYSTEM MODEL

Figure1 (Right) shows TWCN scenario modeled in this study. Similar to HWCN model, a multi cellular scenario of two tiers of co-channel cells i.e. 19 Base Stations (BS) is modeled in the SLS for TWCN. Since most of the real TWCNs use sectorization and it affects the performance significantly so 3 sectors per BS are modeled to evaluate a realistic performance of TWCN.

Important system design parameters used in the SLS of the TWCN are listed in Table 2. For fair comparison system dynamics and user traffic profile used in TWCN performance evaluation are kept exactly same as used HWCN simulations and are already explained in last section. Table 3 lists the user equipment (UE) simulation parameters used for both TWCN and HWCN systems. WiMAX air interface parameters are also kept exactly identical in the SLS for TWCN and HWCN and are listed in Table 4.

Table 2 Simulation parameters for TWCN

Site to Site Distance	1200m
Number of sectors per BS	3
Number of BS	19
BS Max Tx Power	39dBM
Cell Antenna Gain	14dB
Cell Antenna Type	Parabolic
Cell Antenna Height	20m
Shadowing Mean	0dB
Shadowing Std	8dB
Fast Fading	3GPP SCM, URBAN MACRO
Path loss	45.54+35*log10 (distance meters)

Table 3. Simulation parameters for User Equipment (UE)

User Antenna Height	1.5m
User Noise Figure	9dB
User Antenna Gain	0dB
User Speed	3Km
User distribution	Uniform

Table 4. Simulations Parameters for WiMAX Air interface used in the simulation of both HWCN and TWCN systems

BW	5MHz
FFT Size	512
Guard Time	¼ of Symbol duration
Frequency	5GHz
Coding	CCTB
Coding Rate	1/2
Sub-carrier Allocation Mechanism	PUSC
PUSC carrier allocation Type	Distributed Clusters
Modulation Type	QPSK,16QAM and 64QAM
STBC/MIMO	Off
HARQ	Off
Duplexing Mode	TDD
Frame Duration	5ms
Total OFDM symbols per frame	45
Down link Data symbol count	25
Scheduler	Round Robin

4. PERFORMACNE EVALUATION

The performance of both TWCN and HWCN cellular systems depends on a number of factors. For this study we have evaluated the overall performance and capacity of TWCN and HWCN system models described above while investigating the effect of Adaptive Coding and modulation (ACM), Frequency Reuse factor (FR) and user traffic type.

4.1 Performance Metrics

The performance analysis for HWCN and TWCN is based on the observation of three major system performance metrics namely 1.*soft blocking*, 2. *hard blocking* & 3. *spectrum utilization* i.e. percentage of engaged WiMAX radio resources in a cell. (not to be confused with spectrum efficiency). The number of successful users determines the performance of the system in terms of effective user capacity against the performance metrics observed for that particular system configuration. For each system configuration simulations have been run for a large number of times to get average results on Monte Carlo principle. Results are logged for the central cell on the downlink for the downlink only.

4.2 Performance of HWCN and TWCN

Table 5 shows a representative summary of the average performance results obtained for HWCN and TWCN. The performance metrics are measured with the ACM ON and OFF, for two different user rates i.e. 300 (video downloading), and 13 kbps (VOIP) and FR 1 and 3. The results can be discussed for the effect of following aspects.

4.2.1 Effect of Frequency Reuse

The comparison of soft blocking levels between the TWCN and HWCN under identical system configurations shows that soft blocking in TWCN is much higher than that in HWCN even for same FR. This is because in TWCN due to very small cell size the distance between the co-channel cells is too small to cause a significant decay of interference signal. Further in HWCN since the cells are deployed from an aerial platform, so the leakage of co-channel interference is determined by the overlapping of antenna footprints only. Whereas, in TWCN the propagation direction of horizontally traveling interfering signal is difficult to control even through sectorization due to scatters. These facts help HWCN to be friendlier to a tight spectrum reuse than TWCN particularly for small cell sizes.

It is worth to point that advance features of 4G standards namely Space Time Block Coding STBC, MIMO and partial frequency reuse; might have a potential to improve the GoS with FR=1 in both TWCN and HWCN. Further, radio resource allocation with co-ordination among co-channel cells (i.e. central resource scheduling to minimize interference) can also be exploited to avoid interference and improve the performance while adhering to tight frequency reuse. While the first approach is more easily applicable in TWCN second approach has very much potential particularly in case of HWCN because all the BS's i.e. HWCN antennas are spatially co-located in this case. This makes the cell co-ordination technically much easy and less costly in terms of signaling overhead. We would like to point that the investigation of these interference avoidance techniques are potential areas to extend this study in future.

4.2.2 Effect of ACM

A comparison of throughputs with ACM ON and OFF for the two systems under identical conditions shows that ACM brings much larger gain in throughput in case of TWCN compared to HWCN for identical configuration of the two systems. (How ACM brings this gain is explained in detail in [12] and will not be discussed here). The difference in throughput gain brought by ACM in the two systems can be interpreted analyzing the cumulative distribution of SINR in TWCN and HWCN shown in Figure 2. From Figure 2, it can be seen that, in TWCN the SINR values span over a large range compared to those in HWCN. This difference in SINR profile of two systems come from different propagation characteristics of the two systems as explained in section 4.2.1 Since the RSL in HWCN changes much slowly along the cell radius compared to that in TWCN (compare left& right figures in Figure1) so, in TWCN there are some users in the coverage area with much larger SINR values compared to HWCN possibly located in the center of cells. This fact can also be observed by analyzing the relative usage of different modulation schemes in the two systems shown in Figure 3. For a given frequency reuse, percentage of users using higher order modulations is larger in TWCN compared to HWCN. Further, as expected, it can be seen that as the FR=1 is increased to FR=3, percentage of user using higher order modulation increases. But this increment is larger for TWCN compared to HWCN for the same reasons explained above. These facts mean TWCN is capable to exploit ACM more fully than HWCN.

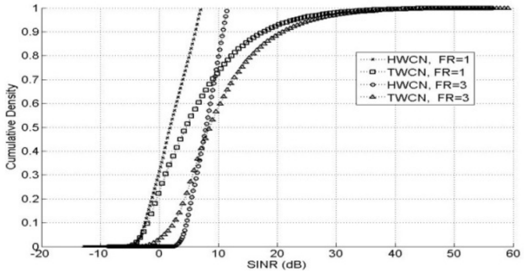

Figure 2: Cumulative Distribution of SINR

4.2.3 *Effect of Traffic Type*

From the simulation results in Table 5. It can be seen that, when ACM is ON, cell throughput is higher with lower data rate per user relative to that with high data rate per user for both TWCN and HWCN. This is because, for a system with fixed amount of radio resources, smaller the data rates per user, larger the number of users in the system and hence higher user diversity. This allows for ACM to play a stronger role hence better cell throughput is achieved. But this increased throughput has a pay off i.e. GoS degrades in case of small data rate per user because of reason explained in section 4.2.2.

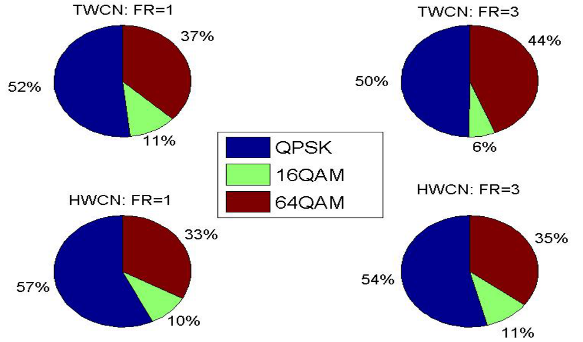

Figure 3:Relative usage of ACM schemes in HWCN & TWCN

5. Relative Cost Analysis

The comparison of absolute costs of HWCN and TWCN is a complex task, but the fact that overall cost of a cellular network is proportional to the number of access point's [15] required per unit area, can be exploited to make it much simpler. An approximate comparison of costs of HWCN and TWCN can be established if a relationship between the average cost of terrestrial Base Station (BS_T) that constitute a TWCN cell and cost of pay load equipment equivalent to terrestrial BS i.e. BS_T in functionality but mounted on HAP i.e. BS_H is established. The cost of a conventional BS_T i.e. C_{TB} can be broken down into some major factors as follows.

$$\mathbf{C_{TB}} = f(\mathbf{PC(h),\ SC(\mathit{l},s),\ HC(t),\ OMC}) \qquad (1)$$

Table 1: Summary of simulation results

FR	Traffic	ACM	No. of UE		Soft blocking		Cell Thr (Mbps)	
			H	T	H	T	H	T
1	VOIP	OFF	108	88	10.8	31.32	1.4	1.1
		ON	215	256	9.7	32	2.8	3.3
	Video	OFF	4	4	10	12	1.2	1.2
		ON	7	10	5	16.67	2.1	3.0
3	VOIP	OFF	119	118	2.2	11.05	1.5	1.5
		ON	270	325	3.1	12.63	3.5	4.2
	Video	OFF	5	5	0	6	1.5	1.5
		ON	9	12	2	6	2.7	3.6

PC=Pole/Tower cost further dependent on its height h
SC=Site cost dependent on location *l* and size s of installation
HC=Hardware cost dependent on amount of traffic t to be handled
OMC=operational and maintenance cost.

Obviously for a BS_H the cost factors PC and SC reduce to zero. These two factors constitute major part of a BS_T. Further the cost factors like OMC and HC can also be expected to reduce many folds for C_{HB} i.e. cost of BS_H compared to that for BS_T. So it is reasonable to infer that

$$C_{TB} \cong F_r \times C_{HB} \qquad (2)$$

Where F_r is the reduction factor by which the C_{HB} is lesser than C_{TB}.. And its exact value depends on the aforementioned factors. Cost of total payload for a HAP in order to deploy a HWCN is then $n{*}C_{HB}$. Where n is number of cells to be deployed from a single HAP. Second major part of the cost of HWCN is the cost of platform itself that carries the payload. This platform can be anything from simple balloon to a very sophisticated air ship. So the cost of platform may vary widely. For the purpose of this analysis, it is convenient to represent cost of HAP platform C_{HP} in terms of cost of conventional terrestrial BS i.e.

$$C_{HP} \cong F_m \times C_{TB} \qquad (3)$$

Where F_m is multiplication factor that means cost of HAP platform can be as low as that of conventional BS e.g. in case of a balloon to as high as many times of the cost of terrestrial BS depending on its complexity. Now the relationship between the per cell deployment cost of HWCN i.e. C_{Hcell} and TWCN i.e. C_{Tcell} can be written as follows.

$$C_{Hcell} = C_{HB} + \frac{C_{HP}}{n} \qquad (4)$$

Using Eq. 2 and 3 in 4.

$$C_{Hcell} = \frac{C_{TB}}{F_r} + \frac{F_m \times C_{TB}}{n} \qquad (5)$$

Since effectively $C_{Tcell} = C_{TB}$ so Eq. (4) can be written as.

$$\frac{C_{Hcell}}{C} = \left(\frac{1}{F} + \frac{F_m}{n}\right) \qquad (6)$$

Figure 4 shows a comparison between the per cell deployment cost of HWCN relative to that of TWCN for a range of possible values of F_r and F_m . Relative cost is plotted for n=7, 19 and 33 to show how the number of cells deployed from the same HAP can affect the system economics. Larger the number of cells deployed per HAP cheaper is the system. But there is technical constraint on the maximum number of antennas that can be mounted on single platform because of spacing and orientation issue. Further there is trade-off here between cost and QoS because the larger the number of antennas mounted on a single platform, higher is the interference among the cells as the overlapping between antenna footprints will increase.

In this paper we have evaluated the performance of HWCN with n=19. So in the following discussion we will consider only this value of n .

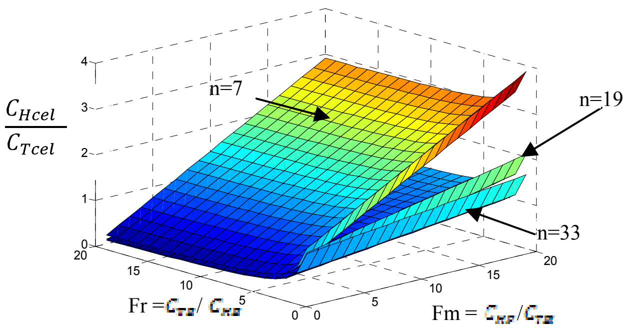

Figure 4: Relative Per cell deployment cost for HWCN and TWCN for range of and and n (number of cells per HAP 7,19 & 33.

6. COMPARISON OF TWO SYSTEMS

The results in Table 6 show the maximum cellular capacity against the respective GoS the TWCN and HWCN systems offer for FR=1 and FR=3. The values are averaged for the different data rates per user to have values close to real traffic that is usually mix of different user rates. As expected tighter frequency reuse increases the capacity but degrades the QoS. There is a degradation in GoS of 16.56 % for capacity increase of about 140 % in case of TWCN as spectrum reuse is tightened from FR=1 to FR=3. Whereas in case of HWCN GoS degrades by only 4% when FR=1 is used in instead of FR=3 while yielding an increase of about 138% in capacity. Reason for this difference in the two systems' behavior is same as explained in 4.2.1. Although the TWCN cell is around $(5/0.6)^2$ =70 times smaller than that of HWCN but the capacity of TWCN is around 90 times higher than that of HWCN. This additional gain in capacity comes because the ACM brings more throughput gain in TWCN than in HWCN as explained in 4.2.2. But this gain in capacity also has payoff as slightly poorer GoS in TWCN that can be seen in Table 6 by comparing the values of GoS for two systems. Figure 5 shows the deployment cost normalized over capacity for TWCN and HWCN scenarios considered in this study relative to each other. HWCN's cost/capacity is plotted for the two extreme values of Fm and Fr in Eq.6. This translates in to the two possible cases of extremely low and extremely high deployment costs for HWCN relative to TWCN. It can be seen that in the best case when Fr=20 and Fm=1, the HWCN deployment solution can be around (1/.131)= 7.6 times cheaper than TWCN for same coverage and capacity with a relatively better GoS. Whereas in the worst case for HWCN's relative cost i.e. when Fr=1, Fm=20 the TWCN based deployment solution can be 2.6 times cheaper than the HWCN.

Table 1: Comparison of Normalized Capacities and Gos

	TWCN		HWCN	
FR	GoS	Capacity(bps/Hz/km^2) m	GoS	Capacity(bps/Hz/km^2)
1	75.66	0.5595	92.65	0.0062
3	90.68	0.23062	97.45	0.0026

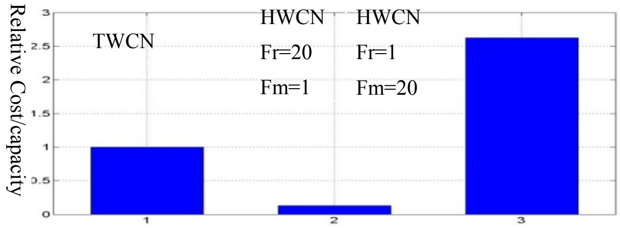

Figure 5: Cost/capacity of HWCN relative to TWCN

7. CONCLUSIONS

The performance and cost evaluation of the two deployment solution show that, HWCN is far more economical solution to deploy a 4G network in areas of low user density where larger cell size is desirable. But for areas with very high user concentration, TWCN with reduced cell size an inevitable solution because of high spectrum efficiency it can yield. But in that case additional measures like MIMO or Relay stations may be required to mitigate the interference to bring the GoS to acceptable level and that may cause some additional cost. So, for dense urban areas, solutions to reduce the cost of TWCN; like Multihop TWCN need to be investigated for economically feasible ubiquitous deployment of 4G and can be focus of future work.

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