Enhancing RF Capacity via Over-the-Air Repeaters

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Introduction
This white paper analyzes the use of RF repeaters to enhance capacity on cellular systems. It is a common misconception that repeaters are only for the purposes of coverage extension or "hole-filling," and do not offer any capacity gain. While this is true for early cellular systems, in the case of 2G+, 3G and 4G cellular systems, repeaters offer more and more significant capacity gains. These gains extend from simply reducing downlink power usage per user, to enhancing the achieved MCS, to further improving MIMO gains under LOS conditions. For today's cellular systems, properly deployed repeaters offer an efficient and low-cost solution for both coverage and capacity problems.

The main effect of an over-the-air repeater is to enhance the SINR of an area, which it achieves in the following ways:

- If an area originally does not have sufficient signal ("coverage hole" or "dead spot"), the result of adding a repeater will be hole-filling, or coverage extension.
- If an area has signals from multiple BSs without a dominant server (known as "pilot pollution" or the "no dominant server" problem), adding a repeater will create a dominant server (by boosting the SINR of the dominant server while suppressing the SINR of others).
- For 4G systems with MIMO, repeaters can create artificial multipath which enhances MIMO gain under LOS conditions.

Capacity versus Coverage Enhancement
The air-link capacity of different types of cellular systems is determined by different factors. If deploying a repeater cannot enhance the capacity factors of a particular system, then the system's capacity cannot be improved, and adding repeaters can therefore only enhance coverage. On the other hand, if some of the capacity factors can be enhanced, then deploying a repeater will enhance both coverage and capacity. Therefore, inferences drawn from one system may or may not be applicable for another system.

In the following sections, we will analyze the effect of repeater deployment on 1G/2G, 2G+, 3G and 4G systems. The capacity impacts are investigated for the following system types:

- 1G: AMPS
- 2G: GSM
- 2G+: CDMA2000 (1xRTT)
- 3G: 1xEV-DO
- 4G: LTE

Note that "capacity" is defined differently for different systems:

- In 1G and 2G systems, capacity factors are primarily for voice, measured in terms of the maximum total number of simultaneous voice calls per sector.
- 3G has a CSD and a PSD; capacity factors for the CSD are primarily for voice, measured in the same way as 1G/2G. 3G PSD is for data, with capacity defined as the aggregate sector throughput.
- 4G is for data only (voice is a special case of real-time data), with capacity measured as the aggregate sector throughput.

The Impact of Repeaters on 1G or 2G System Capacity
For 1G and early 2G cellular systems (AMPS, GSM) where capacities are primarily determined by frequency-reuse factor and the number of time slots per channel, the addition of a repeater offers no capacity gain.

Capacity for 1G Analog Systems (AMPS)
The analog channel does not have advanced techniques to suppress interference, so in order to achieve proper voice quality, the signal power must be much stronger than the sum of all interference powers plus the thermal noise power. For this reason, AMPS systems require the radio channel's SINR >= 18 dB, where SINR is defined as shown in equation 1.

$$SINR = \frac{S}{n_0 + \sum_k I_k}$$

Equation 1

Where S is the received signal power level, n_o is the thermal noise power level and is a constant, and:

$I = \sum_k I_k$ is the received total interference power from all sources.

There are two primary sources of interference: co-channel interference and adjacent channel interference. The interference caused by the adjacent channel is much less severe due to the selectivity of the channel filters. Co-channel interference is the dominant one, so co-channels must be separated as widely as possible. Channels on the same frequency must be physically separated by the variable D (reuse distance) as shown in Figure 1.

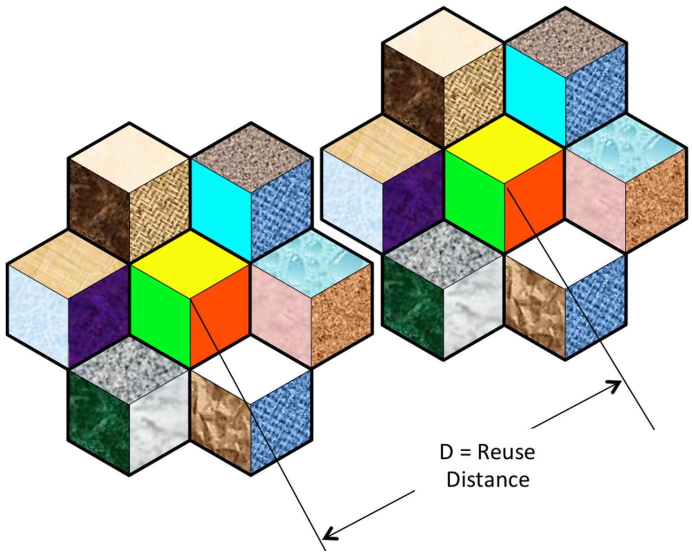


Figure 1: AMPS typically use N=21 (7/21) frequency reuse pattern, where each individual color recurs to indicate a different set of channel frequencies

- In order to achieve the required SINR of > 18 dB on the cell edge, an AMPS system needs a frequency-reuse factor of N=21, i.e.,:
  - The total available channel frequencies must be divided into 21 disjointed sets.
- Since most BSs have a tri-sector configuration, a frequency reuse of 21 means a group of 7 tri-sector BSs, with a total of 21 sectors, i.e., N=21 (or noted as 7/21) frequency reuse pattern, as shown in Figure 1.

With N=21:

- Each sector can only use frequencies from one set, which is about 1/21 = 4.76% of total spectrum (for this reason, the spectral efficiency of AMPS is very low)
- The channel frequencies in each set are chosen so that co-channels and adjacent channels are widely separated. Some examples of frequency planning are shown in Ref.[1].
- It is clear that the network capacity of AMPS is determined by the frequency reuse factor. In order to increase the network capacity for AMPS, there are only two choices:
  (1) Increase the total amount of spectrum so there will be more channel frequencies available.
    - Each AMPS channel bandwidth is 30 kHz, so total number of available channels = (total spectrum) / 30 kHz

  (2) Reduce the frequency reuse factor (N) so each sector can have a higher number of channels.
    - Number of channels per sector = (Total number of available channels) / N
    - The smaller the value of N, the larger the number of channels per sector

Obviously, the deployment of RF repeaters cannot increase the total amount of available spectrum.

The deployment of RF repeaters will only enhance the SINR in the area covered by the re-broadcast antenna; this area is usually a "dead spot," which is typically a smaller area in the network (Figure 2). As a result, repeaters cannot reduce the frequency reuse factor of the entire network.

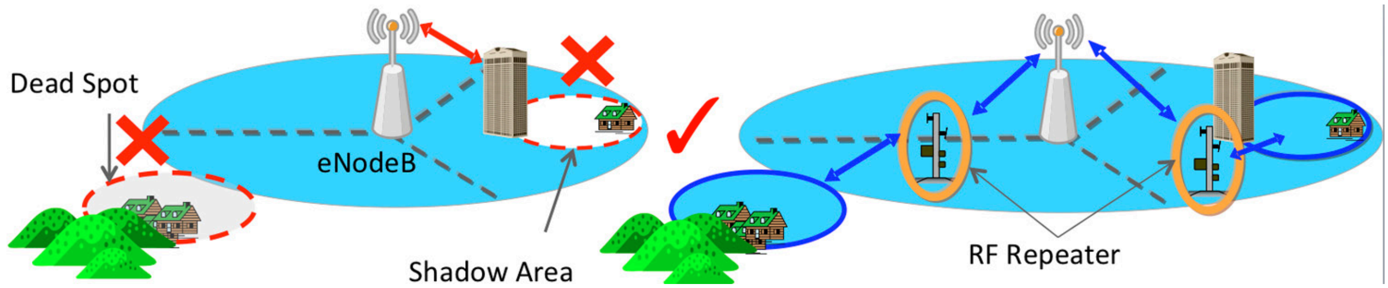


Figure 2: Repeaters can enhance SINR of some dead spots but cannot reduce the frequency reuse factor

Conclusion: Repeaters cannot increase capacity for AMPS; they can only enhance the coverage.

Capacity for the 2G Digital System (GSM)

2G cellular systems use digital technologies. Origionally, there were two families of technologies: the North American TDMA system and the European GSM system. Now that all TDMA operators have merged to GSM. This is the only 2G network in existence today.

GSM uses 200 kHz channel bandwidth with eight time slots per channel. It can handle interference slightly better than AMPS so a smaller frequency reuse factor (N) can be used, typically N=12 (4/12) with tri-sector configuration. N=12 means total number of available frequency channels must be divided into 12 disjointed sets (Figure 3).

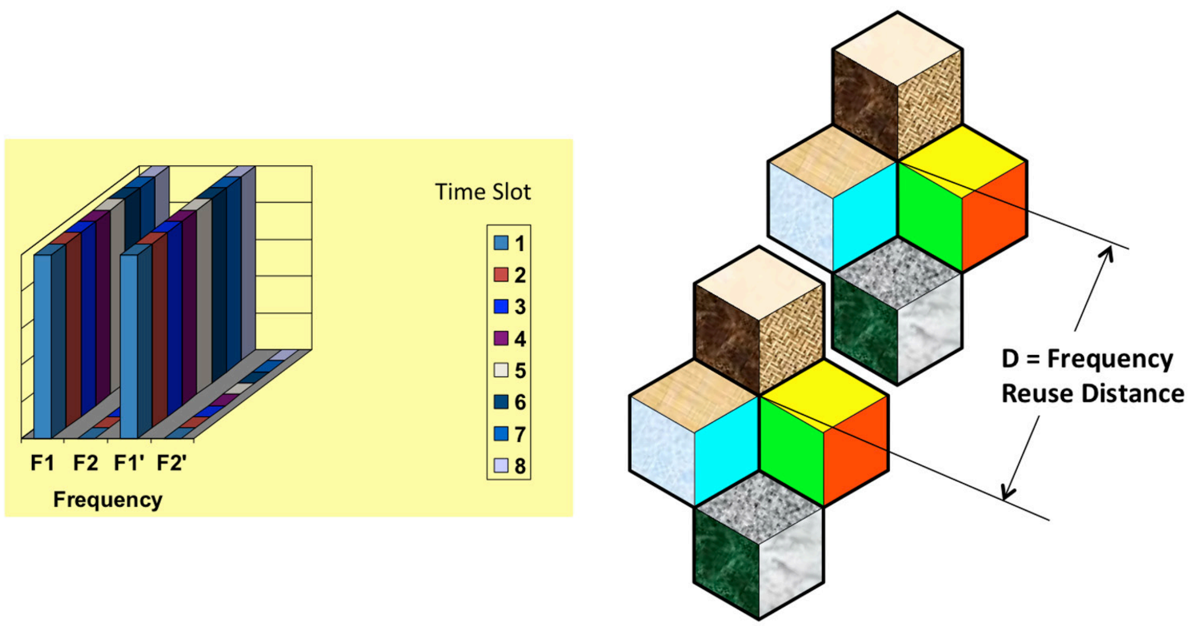


Figure 3: GSM has eight time slots per channel and use frequency reuse of N=12 (4/12), where each individual color recurs to indicate a different set of channel frequencies

Theoretically, there are three factors that affect GSM network capacity, but in reality, only two of these can be changed:

- Total allocated spectrum (variable)
  - Each GSM channel bandwidth is 200 kHz, so the total number of channels = (total spectrum block) / 200 kHz
- Frequency reuse factor N (variable)
  - Number of channels per sector = (Total number of available channels) / N
- Number of time slots per channel (fixed)
  - The number of time slots per channel is fixed by the GSM standard (this cannot be changed so it is not a variable)

Obviously, deploying repeaters cannot change the allocated spectrum, or the number of time slots per channel. Similar to the situation for AMPS, deploying repeaters will only enhance the SINR of relatively small portions of the entire network. This is not enough to reduce the frequency reuse factor of the entire network, so deploying repeaters can only enhance coverage, cannot increase capacity.

Therefore, adding a repeater does not increase the capacity of the GSM network, it only enhances coverage.

Capacity Impacts for 2G+ Systems

There used to be another 2G cellular system called CDMA One (also known as the IS-95 system). All IS-95 systems have now been upgraded to CDMA 2000 (or 1xRTT system). CDMA2000 is considered a 2G+ system, just like UMTS (Rel. 99 and Rel.4).

There are many similarities between CDMA2000 and UMTS:

- They are both spread-spectrum systems which use the universal frequency reuse factor (N=1)
- The capacity equations for CDMA2000 and for UMTS are the same

Although there are some differences between CDMA2000 and UMTS, these differences are irrelevant to the discussion in this white paper. The important point is that the deployment of RF repeaters has the same capacity impact for CDMA2000 and for UMTS, so only CDMA2000 will be discussed. The same conclusion applies to UMTS.

CDMA Reverse Link Capacity

The CDMA reverse link (uplink) capacity has a limit called "pole capacity[1]" which is given by equation 2:

$$N\_user \approx \frac{W/R}{(E_b/N_0)*VAF} * \frac{1}{(1+f)} * Sec$$

Equation 2

Where:

- N_user is the number of simultaneous users per sector to reach the pole capacity
- W is the channel bandwidth, R is the supported data rate, W/R is called processing gain of the spread-spectrum system.
- (E_b/N_o) is the ratio of required signal energy per bit (E_b) to total interference + noise density (N_o), it can be considered as "SINR after de-spread[2]."
- $\frac{1}{(1+f)} < 1$ is the capacity reduction of an imbedded cell due to out-of-cell interference from neighbor cells (Figure 4)
- Sec is a factor due to sectorization: if isolation among neighboring sector were perfect, then three sectors should increase capacity by a factor of 3. In reality, there will always be interference leaking to the neighboring sectors, so the capacity gain for three sectors is less than 3, typically 2.4 to 2.55, so the value of Sec is about 80% ~ 85% (2.4/3 ~ 2.55/3).
- VAF is the voice activity factor for voice link.

The deployment of RF repeaters will not change most of these factors.

1 Normally, the network is operated at 50% ~ 65% of pole capacity.

2 Eb/No = (W/R)*SINR, where SINR is the signal to (interference + noise) ratio before de-spread

First, consider whether or not the repeater affects (E_b/N_o), because this is the SINR after de-spreading, and the repeater is supposed to increase SINR. (E_b/N_o) is the minimum required SINR at the BS receiver, after de-spreading, in order to achieve the required service quality for voice or data. This service quality is determined by the targeted frame error rate (FER). For example, the voice FER is usually kept around 2%. CDMA (or UMTS) uses reverse-link power control to maintain this FER target.

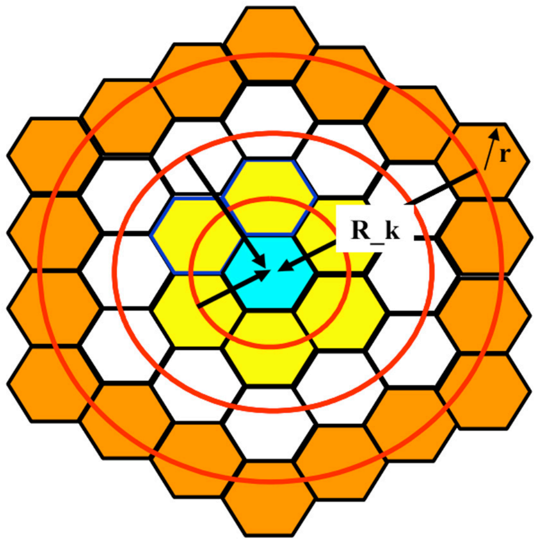


Figure 4: The reverse link capacity of an imbedded cell (blue) is reduced by out-of-cell interference from neighbor cells (yellow, white, orange)

- If the achieved FER from one user is worse than the target (>2%), the BS instructs the MS to raise its Tx power, as a result, the achieved (E_b/N_o) is increased, which reduces FER
- If the achieved FER from one user is better than the target (<2%), the BS instructs the MS to reduce its Tx power, as a result, the achieved (E_b/N_o) is decreased, which increases FER
- CDMA reverse link power control is performed at 800 times per second (UMTS at 1500 times per second) to maintain the FER target

Next take a look at the effect of deploying RF repeaters.

- Before the repeater is deployed: users in a cold spot will have very weak coverage, so terminals have to transmit high power in order for their signals to have sufficient (E_b/N_o) at the BS receiver to maintain the FER target. Since the maximum Tx power from CDMA terminal is 200 mW, if this limit is reached, reverse link power control can no longer raise the terminal's Tx power level. As a result, the FER target at the BS receiver cannot be met. If the FER exceeds a certain threshold longer than a certain time limit, the call will be dropped. In this case, the "cold spot" becomes a "dead spot" with no service. In other words, the user at this location has exceeded the "reverse link budget limit."
- After the repeater is deployed: the SINR will be significantly enhanced. The reverse link power control will instruct the terminals to reduce their Tx power to keep the same (E_b/N_o) at the BS receiver to maintain the FER target. The result is that both (E_b/N_o) and FER are kept at the same level (the target levels) but the terminal's Tx power level is significantly reduced. Effectively, this is as if the users are moved closer to the BS. In other words, the repeater improves the link budget to the cell edge user, because it effectively reduces the path loss between the BS and cell-edge users.
- The net effect of repeater addition on the reverse link capacity of single-cell CDMA is that it does not change the capacity (because (E_b/N_o) is kept the same by the reverse link power control), but the reverse link budget is improved, since the terminal is transmitting less power, so the user can move farther away from the base station. This means coverage improvement, but no capacity gain.

The only factor in the Eq.[2] that gets improved is the factor $1/(1+f)$. In an imbedded cell, reduced user Tx power will reduce out-of-cell interference to neighbor cells, which in term, improves $1/(1+f)$. This is a very minor improvement, because out-of-cell interference is the sum of uplink interference from all users from all neighbor cells (Figure 4). Reducing the Tx power level from users in a cold spot due to the addition of repeaters will only reduce the overall out-of-cell interference slightly so a very minor improvement to $1/(1+f)$.

Conclusion: Repeater only has a very minor impact on CDMA reverse link capacity, it is through the reduction of cell-edge users' Tx power level which reduces out-of-cell interference.

CDMA Forward Link Capacity

As shown by Holma and Toskala [2], CDMA forward link (downlink) also has a pole capacity. However, in real networks, the operation point is better approximated by empirical formula shown in Equation 3.

$$N\_user \approx \frac{P_{Call\_Block} - P_{OverHead}}{P_{Link} * SPU}$$

Equation 3

Where:

- $P_{OverHead}$ is the total power allocated to the forward overhead channels (Pilot, Synch and Paging)
- P_{Call_Block} is the maximum allowed downlink power usage (total overhead channel power + total traffic channel power)[3].
- P_{Link} is the average forward link power usage per traffic channel (taking into account the voice activity factor)
- SPU is the soft + softer handover factor (so each active user will have more than one link on average)

The physical meaning of Equation 3 is straightforward: ($P_{Link}*SPU$) represents the average[4] traffic channel power used by one user; (P_{Call_Block} – $P_{OverHead}$) is just the total power available for all traffic channels, as shown in Figure 5. When this total power is used up, the sector has reached its forward link capacity limit. Any new call setup will be rejected.

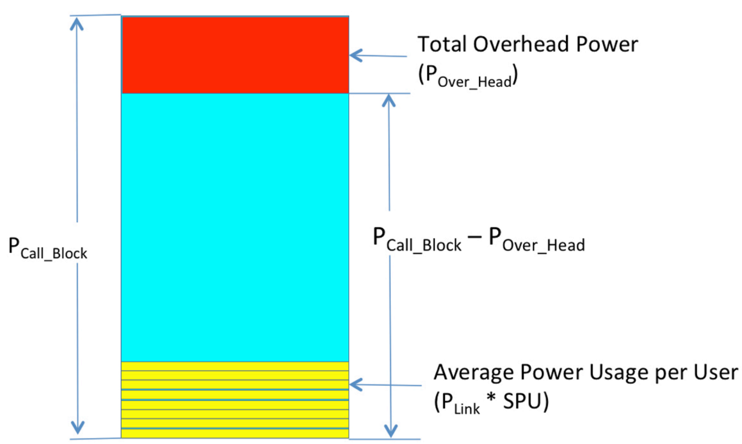


Figure 5: Illustration of CDMA forward link capacity

3 If at any instance the PA power usage exceeded $PCall\_Block$ the sector will experience forward link power limiting (in order to protect the PA). In this case, power for every channel will be reduced, which is very undesirable because the forward link power control will try to raise the power again. Effectively, Power Limiting and Forward Power Control "fight" each other, which can cause instability. For this reason, total forward link power usage should not reach $PCall\_Block$. So $PCall\_Block$ means "maximum power threshold that should not be exceeded."

4 Note that users located near the BS will need very little power; users located near the cell edge will need very high power. Average power per link represents the average power usage, taken from all users (center, middle or cell edge) within the sector.

One may ask: to enhance the forward link capacity, why not simply use a larger PA so ($P_{Call\_Block} - P_{OverHead}$) is higher? A larger PA may or may not improve the capacity, depending on the interference scenario:

- For interference-limited environments (urban, dense urban): increased PA power will also increase the out-of-cell interference, so the BS will need to allocate more forward link power to users to achieve the same SINR. As a result, both numerator ($P_{Call\_Block} - P_{OverHead}$) and denominator (PLink) will increase and the ratio (capacity) is not improved.
- For coverage-limited environments (rural, highway): in the low interference scenario, increasing the PA power will enhance forward link capacity.

Now let's look at the impact of repeaters on CDMA forward link capacity.

- Before a repeater is deployed: users located under poor coverage (cell edge or cold spots) will need very high forward link traffic power in order to achieve the required downlink SINR. In terms of power usage, cell-edge users are very "expensive," in the sense that power allocated to one cell-edge user can serve many cell-center users. A few users located in a poor coverage area will deplete the PA power and "drag down" the overall capacity. Consequently, serving a large number of cell-edge users will make the overall capacity very low.
- After the repeater is deployed: Due to enhanced SINR (or improved forward link budget), the cell-edge users need much less power from the BS, as if they are moved much closer to the cell center. This effect of reducing PA power usage significantly increases forward link capacity.

The effect of deploying a repeater is to enhance the link budget. The effect is as if the users located in cell edge are moved much closer to the cell center.

- Single-cell CDMA reverse link capacity is independent of user location, i.e., moving users closer to the cell center does not increase reverse-link capacity. In an imbedded cell within a network, the reduced Tx power level from the cell-edge users will reduce out-of-cell interference to other cells, resulting in a minor improvement of overall reverse-link capacity.
- CDMA forward-link capacity is very sensitive to user location. A cell with more users located near the cell edge will have much lower capacity compared to a cell with most users located near the cell center. Therefore, deploying repeaters will significantly enhance forward-link capacity.
- Field data shows that the overall CDMA network capacity is most often limited by the forward-link capacity. Therefore, deploying repeaters can enhance overall CDMA capacity.

Conclusion: Deploying repeaters can enhance the overall 2G+ network capacity.

Impact of Repeaters on 3G System Capacity

As mentioned previously, 3G (PSD) and 4G systems are primarily for data (voice is just a special case of real-time data). Capacity is represented by aggregate sector throughput. Anything that increases sector throughput enhances capacity.

SINR vs. Achieved Peak Rate

For 3G systems (1xEV-DO, HSPA), the capacity gain from repeaters is more direct since repeaters improve the achieved SINR, thus directly affecting the achieved MCS.

Again, HSPA and 1xEV-DO are very similar; therefore we only discuss the repeater's effect on 1xEV-DO capacity. Similar arguments apply to HSPA.

The following table shows the achieved downlink data rate as a function of SINR[5]:

Data Rate (kbps)	Traffic Ec/Nt (=SINR) (dB)
38.4	-10.5
76.8	-7.5
153.6	-4.5
307.2	-2.0
614.4	1.0
921.6	3.3
1228.8	5.0
1843.2	9.2
2457.6	11.5

Table 1: 1xEV-DO DL Rate vs. SINR

Note that from the above table, the maximum rate is about 64 times higher than the minimum rate; the required SINR to achieve the maximum rate is about 22 dB higher than the required SINR for the minimum rate. One can see that if the SINR values in a cold spot can be enhanced as a result of repeater deployment, the achieved data rate will increase significantly.

Figure 6 shows the achieved peak downlink rate versus the distance to the cell center (Flat-Earth Model). It shows that the closer the users are to the cell center, the higher the received downlink SINR.

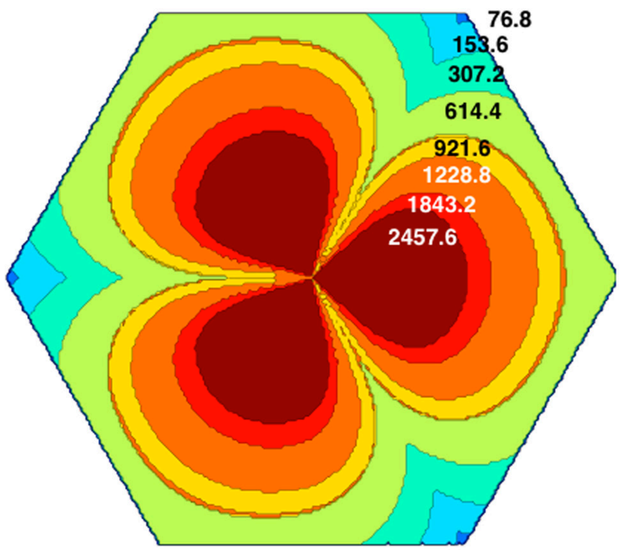
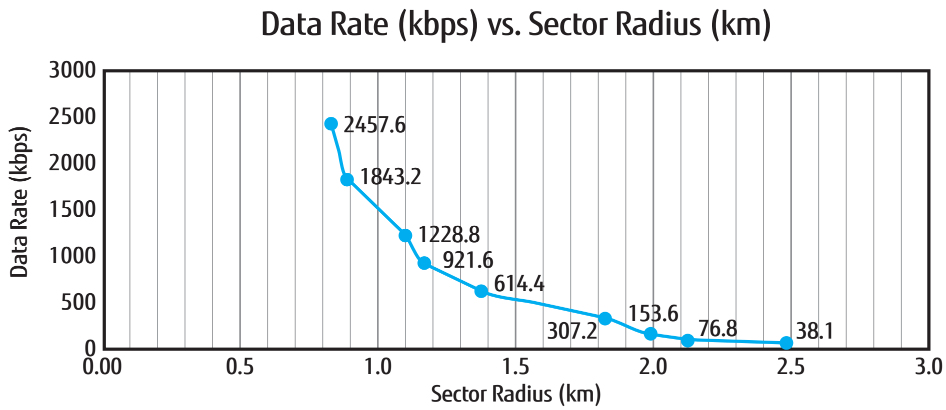


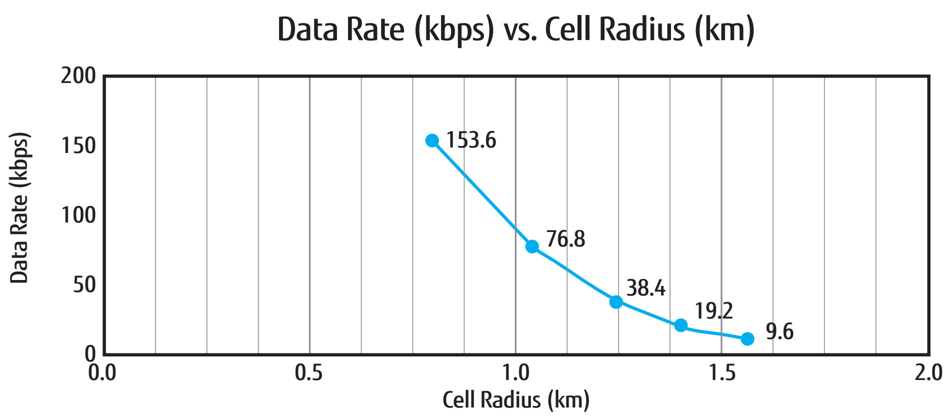
Figure 6: Single-User Data Rate Distribution in a 1xEV-DO Cell

5 For simplicity, we use 1xEV-DO Rev-0 as an example. 1xEV-DO Rev-A has similar relation of "SINR vs. Rate," except DO-Rev-A is more complicated. The conclusion is the same in both cases.

Figure 7 shows the achieved peak data rate for a single user as a function of its location to the cell center (for a typical situation). It is clear that the farther away the user is from the center, the lower the achieved data rate.



(a) Forward Link (downlink)



(b) Reverse Link (uplink)

Figure 7: The peak data rate of a single user as a function of distance to the cell center

As previously mentioned, the effect of deploying repeaters is to enhance the SINR of cell-edge/cold spot, which is equivalent to bring users from the cell-edge/cold spot to much closer to the cell center. Figure 8 shows the simulation results of SINR distribution as a function of a single repeater's location as it moves toward the cell edge. One can see the result of cell-edge SINR increase (comparing yellow points with blue points). This increased SINR directly translates into an increased data rate, thus the deployment of a repeater can significantly enhance the network capacity.

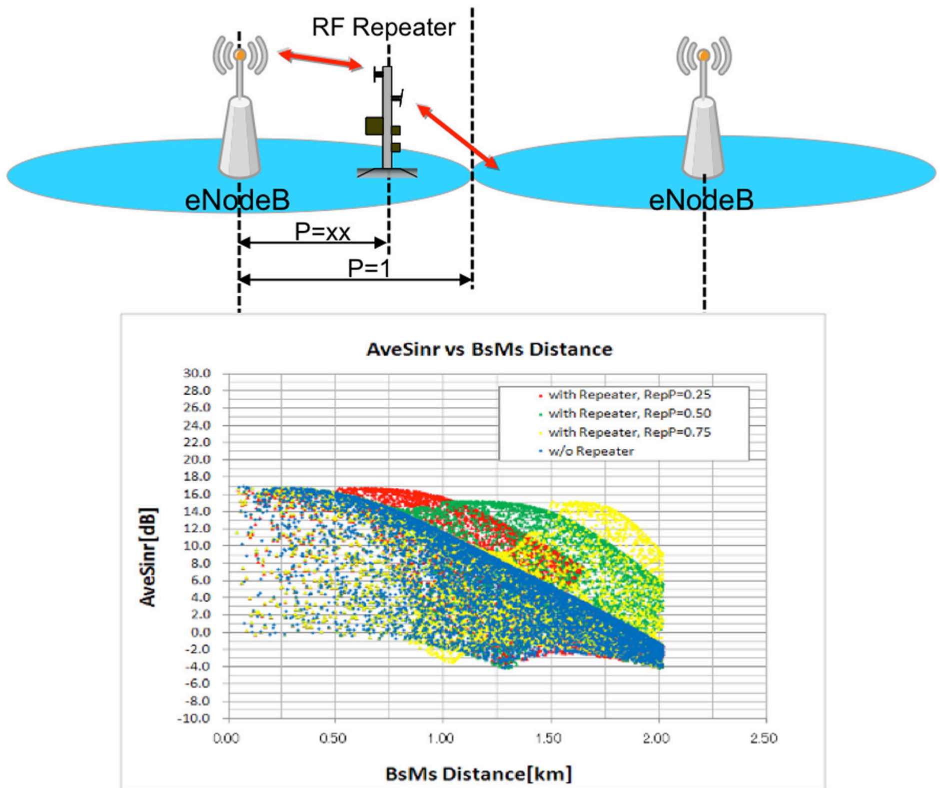


Figure 8: SINR distribution versus repeater locations

Figure 9 shows simulation results of SINR contours in a tri-sector cell with two repeaters deployed per sector and with eight repeaters deployed per sector. Figure 10 shows the cumulative distribution function (CDF) of spectral efficiency improvements due to deployment of two or eight repeaters per sector [3].

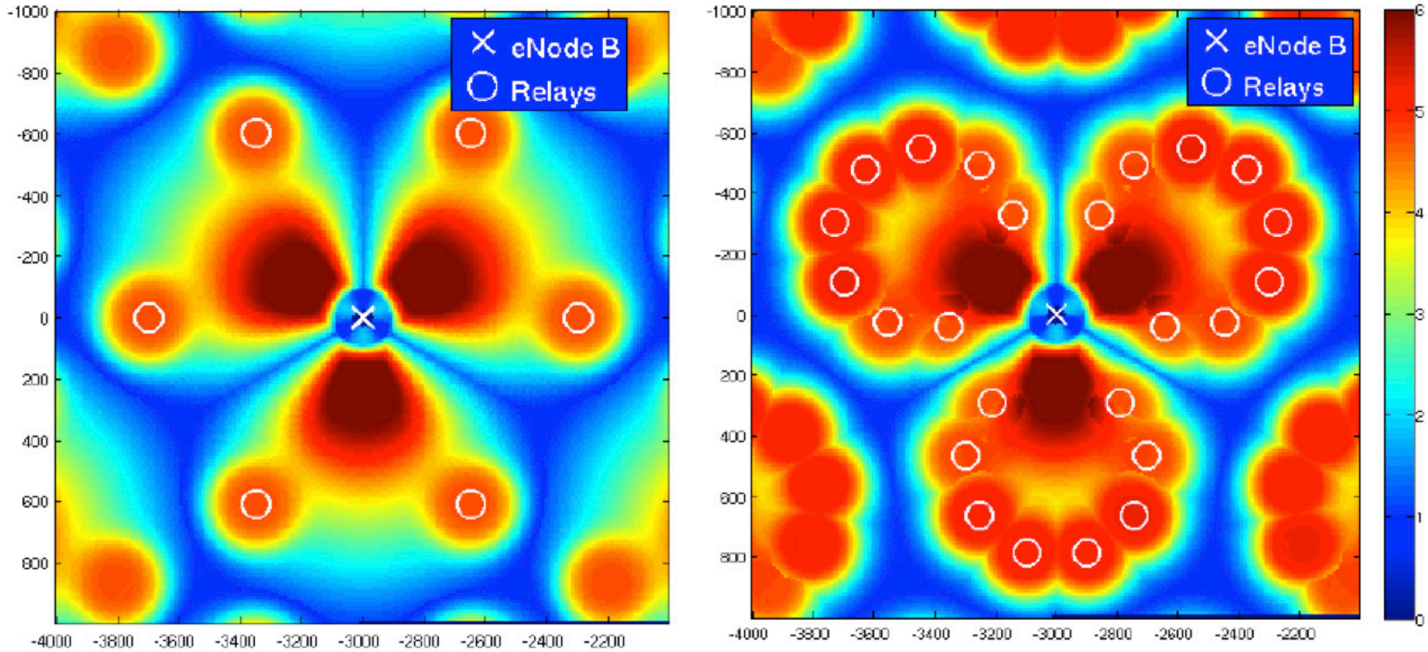


Figure 9: Cell-edge SINR improvement due to deployment of two repeaters (left) and eight repeaters (right)

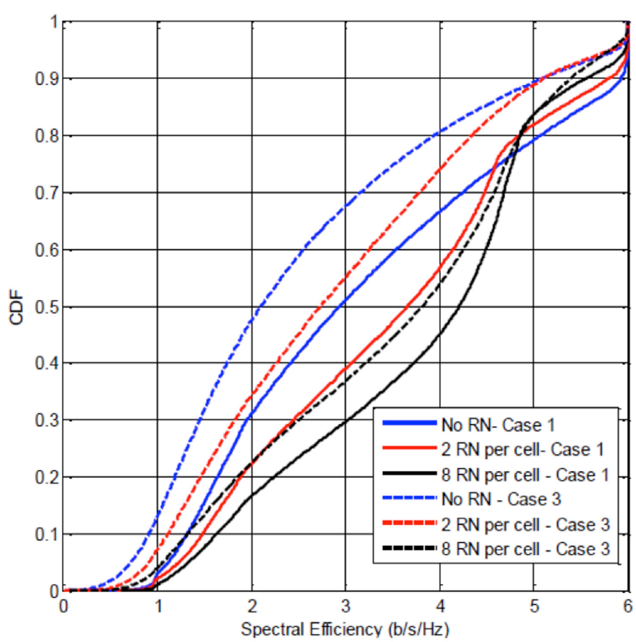


Figure 10: Spectral efficiency gains due to repeater deployment

Figure 11 compares the cell-edge service outage probability with and without repeater deployment. One can see that repeaters significantly improve cell-edge SINR and thus reduce outage probabilities [4].

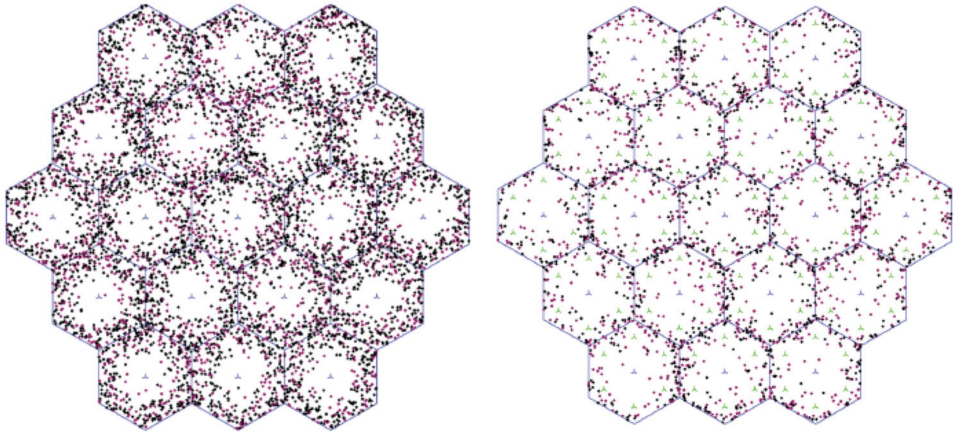


Figure 11: Comparison of cellular outage performance (black dots denote UE subject to outage) (left). No repeater deployed (right) multiple repeaters deployed near the cell edge.

The Impact of the Scheduler's Service Time Allocation

In addition to the increased MCS due to enhanced SINR, there is another factor that can further increase the aggregate sector throughput, and this is the effect of the scheduler's service time allocation.

All 3G and 4G systems use schedulers to determine the percentage of RF resources to allocate to each user. In the case of 3G, this resource is a percentage of allocated service time. Under a "fair scheduler[6]," each user gets an equal percentage of service time. Under a full-queue model, if there are N (N>1) users in a sector, each user get 1/N as much service time. This means each user's throughput is proportional to the achieved MCS, and the aggregate sector throughput is expressed in Equation 4.

$$SectorTput = \sum_{k=1}^{N} \frac{1}{N} * (MCS)_k = \frac{1}{N} \sum_{k=1}^{N} (MCS)_k$$

Equation 4

Where $(MCS)_k$ is the achieved MCS from $user_k$ at location k, and achieved MCS is determined by the achieved SINR at location k.

However, a full-queue model is often not a good representation of most real-life data applications. Most data applications (e.g., Web browsing, short messages) have finite data volumes. In this case, an "equal-volume model" is a better approximation of the real situation. If all users have same amount of data to download, then:

- Users located near the cell center will complete downloads rapidly because of the high data rate they achieve; after download completion, these users will no longer request resources. So the cell-center users will spend very little time requesting air link resources.
- Users located near the cell edge, due to the low data rate they achieve, will spend much longer times trying to download content. So they spend larger amounts of time requesting airlink resources. The scheduler has no choice but to spend a higher percentage of time servicing cell-edge users.
- The result is that the faster the date rate a user can achieve, the smaller the percentage of service time; the slower the data rate a user has, the higher percentage of service time. The net effect is that the scheduler will spend the most time serving users on the cell edge; as a result the aggregate sector throughput will be significantly "dragged down" by those users (Figure 12).

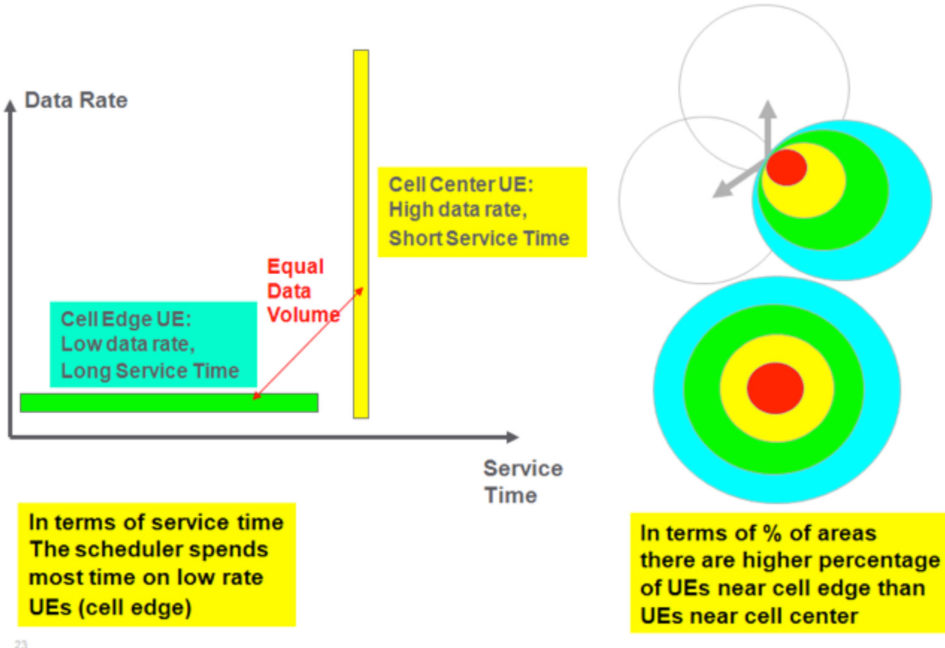


Figure 12: Under the equal-volume model, the scheduler spends most time serving the cell-edge users

Repeater deployment significantly increases the achieved data rates for users on cell edges/cold spots, so these users can download much faster and request less time resources, which relieves the scheduler's service time allocation. This means that the capacity enhancements due to repeaters will be even more significant than just the increased MCS.

Conclusion: Deploying repeaters will significantly enhance the capacity of 3G systems. The capacity enhancement is much more significant than that for 2G+, due to the enhanced MCS and improved scheduler service time.

Repeater's Impact on 4G System Capacity

For 4G systems (WiMax, LTE), the effects of repeater's capacity enhancement due to increased MCS and improved scheduler service time allocation are the same as those for 3G systems. However, there is one more effect that can potentially boost 4G capacity gain even further, due to the fact that repeaters enhance the MIMO gain under LOS conditions. MIMO technology is one important factor that gives 4G extra-high capacity.

MIMO technology relies on statistically uncorrelated channel coupling in order to effectively retrieve the multiplexed transmitted data. One way to achieve uncorrelated channel coupling is through reflections of local scatters. On the other hand, MIMO gain can only be achieved in areas with high SINR values, i.e., areas near the cell center. However, areas near the cell center often have LOS condition, and LOS condition is not desirable for MIMO because the channels under LOS are highly interdependent[7].

So in order to achieve the maximum MIMO gain, there are somewhat conflicting requirements:

- High SINR
- Non-LOS (so it is multipath rich)

7 "Correlation" cannot be properly applied to these LOS channels, since they are increasingly deterministic as the Rician K-factor increases.

As a result, the actual achieved MIMO gains from a real network are often much smaller than estimates based on simulations, because the percentage of areas in a real network with both high SINR and non-LOS may not be that high.

One way to solve this dilemma is to use over-the-air repeaters operating as "active reflectors" to improve the richness of the multipath environment, thereby reducing the effective Rician K-factor without blocking the LOS component, and orthogonalizing the channel matrix. This is the so-called "repeater-assisted capacity enhancement (RACE)." Note that under RACE, the repeater's main function is not enhancing the SINR, but acting as active reflectors to create "artificial multipaths."

Figure 13 illustrates the case of 4x4 MIMO with the addition of three repeaters to create artificial multipath.

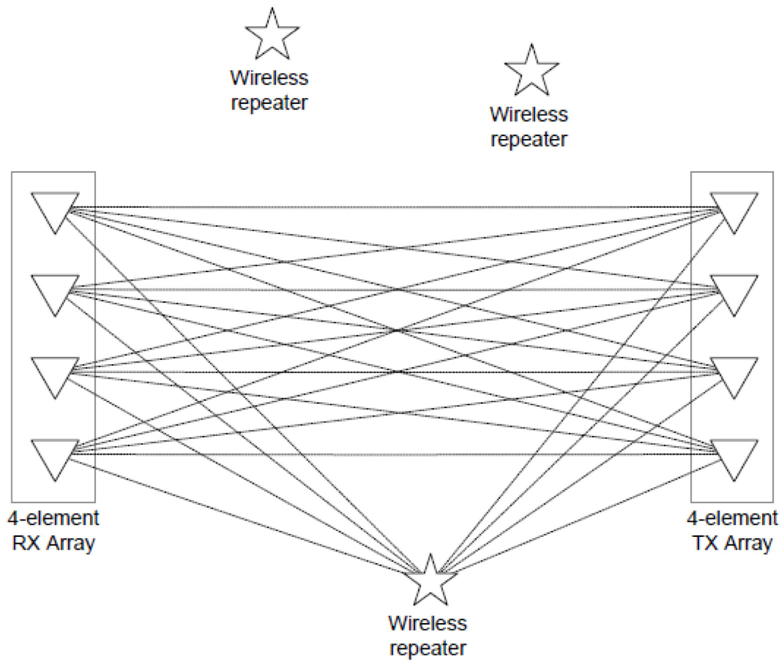


Figure 13: Repeater can add artificial multipath to areas with LOS condition

Figure 14 shows a set of simulation results of MIMO capacity [5] and positioning metric [6] of a 4x4 MIMO under LOS condition. The positioning metric is a mathematical quantity that can give the optimum locations of the repeaters. The metric is maximized when Tx and Rx steering vectors are mutually orthogonal. As shown from Figure 10 (right), there are several "light spots" (marked 1, 2, …9) in the positioning metric; if repeaters are placed in these light spots, the achieved MIMO capacity is at its maximum.

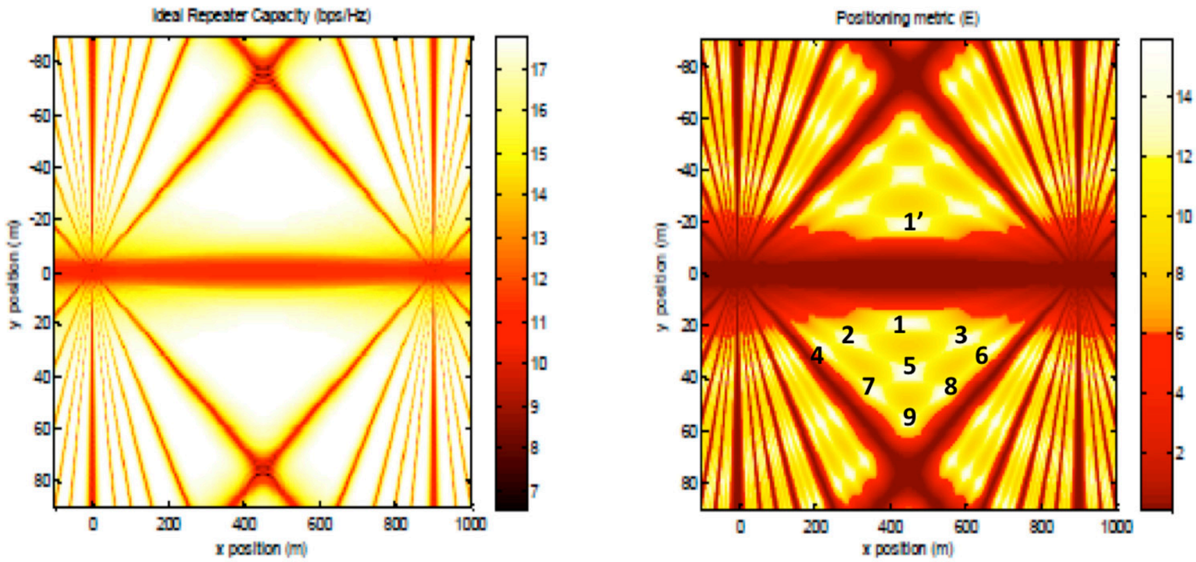


Figure 14: MIMO capacity versus locations (left): the lighter the color, the higher the capacity. Positioning metric versus locations (right). The nine light spots represent the optimum locations for repeaters.

Figure 15 shows the result of new capacity if two repeaters are placed at the optimum locations 1 and 1' (x position = 450 m, y position = -19 m and + 19m). Note that the white color in Figure 15 (Left) represents 34 bps/Hz, about twice as high as the white color in Figure 14 (=17 bits/Hz). This indicates the new capacity is significantly higher after the addition of two repeaters at the optimal locations.

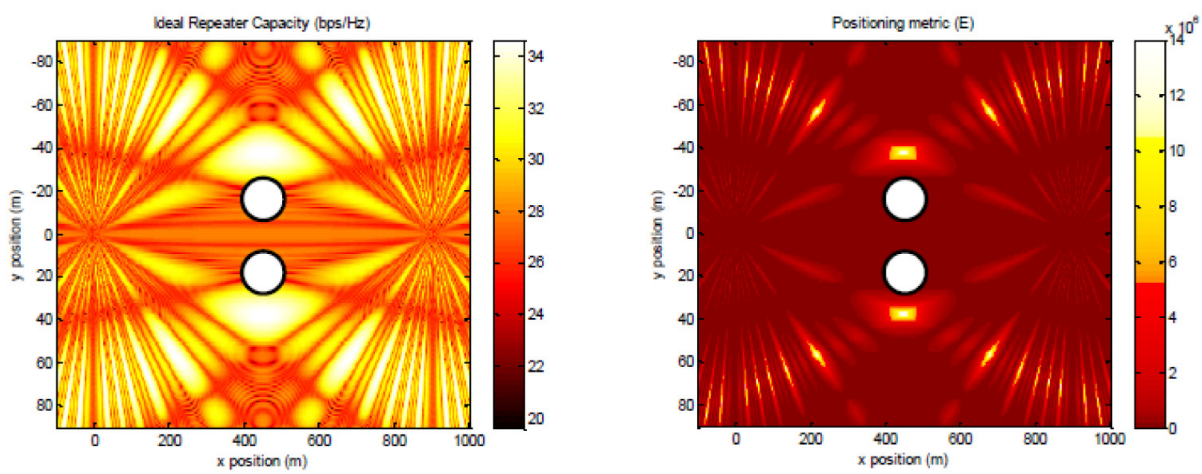


Figure 15: Result of adding two repeaters at optimum locations: new MIMO capacity versus locations (left). New positioning metric (right).

Since in real networks the UE locations are somewhat randomly located, it is impossible for the repeater's locations to be optimal for all UE locations. The following results show that even if the repeaters are not placed at the optimum location (y=-38 m and +38m in this example), the achieved MIMO capacity gain is still significant. The white color in the capacity plot in Figure 16 represents 32 bits/Hz which is slightly lower than 34 bits/Hz in Figure 15. This means that most users under LOS conditions will benefit from the addition of repeaters even if the repeaters are not located at the best possible locations.

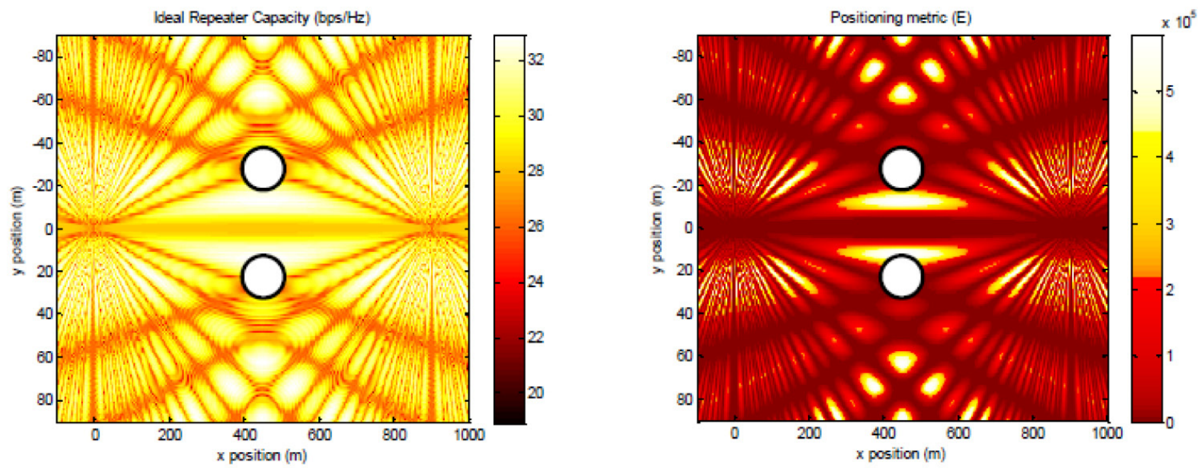


Figure 16: Result of adding two repeaters at sub-optimum locations: New MIMO capacity versus locations (left). New positioning metric (right).

Summary

For 1G and 2G cellular systems, network capacity is determined by the frequency reuse factor. Deploying repeaters can only enhance SINR in localized areas ("cold spots") which is not sufficient to reduce the frequency reuse factor for the entire network. Consequently, for this kind of system, repeaters can only enhance coverage, not capacity.

All newer cellular networks, starting from 2G+, use a frequency reuse factor of one. 2G+ capacity is usually limited by the forward-link capacity which is a strong function of user distribution. Repeaters effectively bring users closer to the cell center, which enhances capacity.

3G and 4G capacities are measured by aggregate sector throughput. For these systems, the capacity is a strong function of the achieved SINR. Any effect of increasing SINR, even if it is only for a localized area (e.g., "cold spot"), will enhance the overall sector throughput (capacity). This is because aggregate sector throughput is contributed from every part of the network, so throughput increases are significant regardless of their location of origin.

For 3G and 4G systems that use schedulers, enhancing the SINR for the cell edge and cold spots has more significant capacity gain due to the effect of the scheduler. Regardless of priorities, schedulers have strong tendencies to serve the users under poor coverage, thus a smaller number of cell-edge users can significantly pull down the overall capacity. Eliminating these poor coverage areas will have a more significant capacity effect than most people realize.

For 4G systems using MIMO, properly deployed repeaters can create artificial multipaths for areas under LOS conditions which can further increase MIMO gains. Therefore, in addition to helping cell-edge users by boosting the cell-edge SINR, repeaters can enhance cell-center user throughput by enhancing the MIMO gains.

In conclusion, "repeaters are for coverage enhancement only" is a misconception in today's networks. The more advanced the technology becomes, the more significant will be the capacity gain from repeaters. In LTE-advanced (3GPP Release 10), repeaters will evolve into relays. Relays can be considered much smarter versions of repeaters. Relayed networks have a "double star" architecture which offers significantly higher capacity compared to today's networks with "single star" architecture. When changing from today's classic repeaters to future relays, only the "box" needs to be changed; antennas, cables, towers, sites, and so on, do not need to be changed. This makes repeater deployment very attractive from an evolution point of view: today's repeaters can be easily upgraded to tomorrow's relays.

Acronyms

AMPS	Advanced Modulation Phone System
BS	Base Station
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CSD	Circuit Switched Data
EV-DO	Evolution Data Optimized
FER	Frame Error Rate
GSM	Global System for Mobile (communications)
HSPA	High-Speed Packet Access
LOS	Line of Sight
LTE	Long-Term Evolution
MCS	Modulation and Coding Scheme
MIMO	Multi-Input Multi-Output
mW	Milliwatts
PSD	Packet Switched Data
RF	Radio Frequency
RTT	Radio Transmission Technology
SINR	Signal-to-Interference/Noise Ratio
TDMA	Time Division Multiple Access
UE	User Equipment
UMTS	Universal Mobile Telephone System

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FUJITSU NETWORK COMMUNICATIONS INC.
2801 Telecom Parkway, Richardson, Texas 75082-3515
Telephone: (972) 690-6000
(800) 777-FAST (U.S.)
us.fujitsu.com/telecom