Siting Mobile Phone Base Stations:
a GRASS application on location selection

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Abstract

Because of the basic requirement to offer good communication quality, the mobile phone system providers are constantly siting base stations as needed in order to provide enough signal coverage and strength.

This paper first discusses those issues related to siting mobile phone base stations, such as the location, the quantity, the radio signal coverage, the channel capacity of each base station, etc. It then uses GRASS, combined with location and allocation theory, to analyze the current issues of siting mobile phone base stations and develop a heuristic solution based on the line-of-sight analysis.

Finally a small town in Taiwan is used as the study area to examine the effectiveness of the developed solution.

1 Introduction

1.1 Background

In many countries the mobile phone has become an indispensable tool of communication. However, a mobile phone (handset) cannot work by itself. It relies on a system of infrastructure to support it. Among those supporting elements in the system, the mobile phone base station is the one that is most relevant to not only its users but also other general population. On one hand, users of mobile phone handsets need a sufficient number of base stations at appropriate locations to maintain acceptable quality of service. On the other hand, because mobile phone radiation and health concerns is still a controversial issue [8], health hazards of base stations frequently overshadow people's mind who live in the vicinity of the stations.

In Taiwan possible health hazards of base stations often make siting them a fierce issue and sometimes a headline in local news reports. There are three reasons. First, because almost all urbanized areas in Taiwan are densely populated and thus occupied by high-rise buildings that decrease or even block the radio signal, the number of base stations have to be increased.

Second, unlike the landlords of base stations, people who live in the vicinity of the stations have to bear the potential hazards of higher radiation without any compensation. Therefore they will usually protest the installation of a base station in their neighborhood, and sometimes successfully force the station to relocate. This makes siting base stations qualified as NIMBY (not in my back yard). However, duo to the basic requirement to offer acceptable quality of service, the mobile phone system providers have no choice but to constantly site base stations as needed in order to provide enough signal coverage and strength.

Third, probably because of intense competition among mobile phone system providers, they usually treat their base station sites and siting process as trade secrets. This and the previous reason make the base station siting issue never resolves in an open and fair manner to all affected parties.

1.2 Objectives

This paper describes the development of an open-sourced solution to siting mobile phone base stations. It hopes that through such a free and readily available solution, siting base stations will no longer be a black box but can be discussed openly and objectively. In addition, it also hopes that this paper can serve as a test report of the current state-of-arts of GRASS for all interested parties, which is important in the continuing improving process of open-source software development. The remaining parts of this paper will first explain the basic factors related to siting mobile phone base stations. It will then go on to explain how to use GRASS to develop a heuristic solution based on the line-of-sight analysis. The solution is then applied to a study area, a small town in central Taiwan, to examine its effectiveness.

2. Basic Concepts

2.1. Mobile phone system

Although this paper uses the term mobile phone instead of cellular phone or cell phone, all discussion here do not include any device that does not have a cellular network [5], such as satellite phones. Here the mobile phone system refers to the telecommunication system formed by (mostly) handheld electronic devices connect to a cellular network of base stations, which in turn is interconnected to the public switched telephone network (PSTN) [7].

By this definition, a simplified view of the mobile phone system consists of three basic facilities: mobile station (MS), base station (BS), and mobile telephone exchange (MTX) [2], as shown in Figure 1. A BS is the interface between wireless signal, which is used to communicate with MS, and wired signal, which is used to communicate with MTX. Therefore BS plays a key role in a mobile phone system.

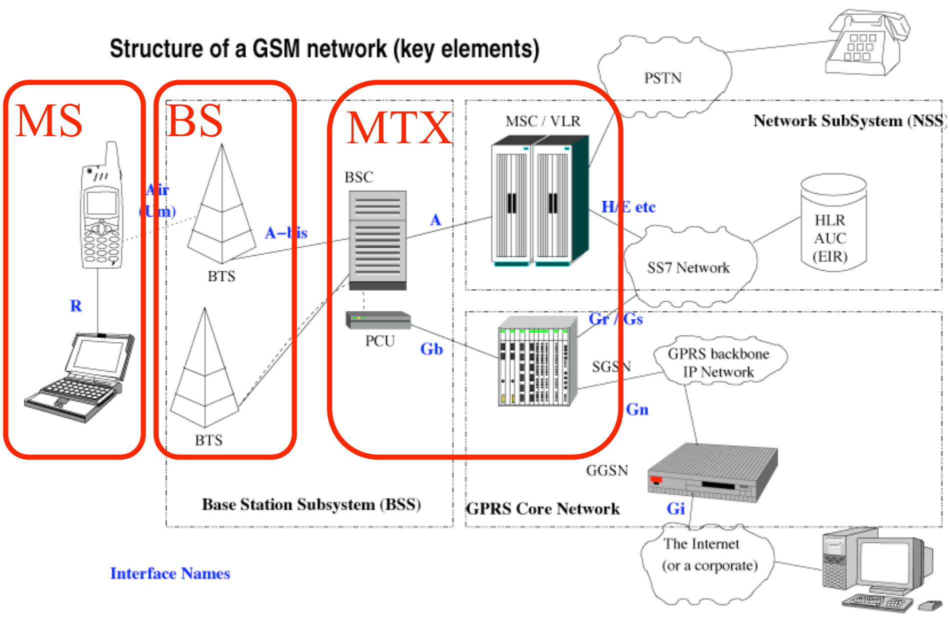

Figure 1 Key elements of a mobile phone system (courtesy of Wikipedia)

2.2 Base station characteristics

A BS is characterized by two factors, its radio signal strength and its channel capacity. Radio signal strength of a BS determines its coverage, i.e. how far a MS can be away from it, while channel capacity determines how many MS it can serve concurrently. In a perfect situation where MS distribute in a flat terrain evenly, a number of BS that is required to serve the MS will form a honeycomb pattern with each BS in the center of a cell, as shown in the right side of Figure 2. That is why the mobile phone is also called cellular phone.

However, this is seldom the case. In most real world situations, neither terrain, especially the built environment, is flat, nor people who use those MS will locate in an evenly distributed fashion. Siting BS is thus not a simple task of drawing a regular honeycomb grid on the map. It has to take into consideration those factors mentioned above, such as signal strength, channel capacity, terrain, and distribution of MS, in order to provide acceptable quality of service. This is how GRASS, which is a powerful open source geographic information system (GIS), can help [1][3].

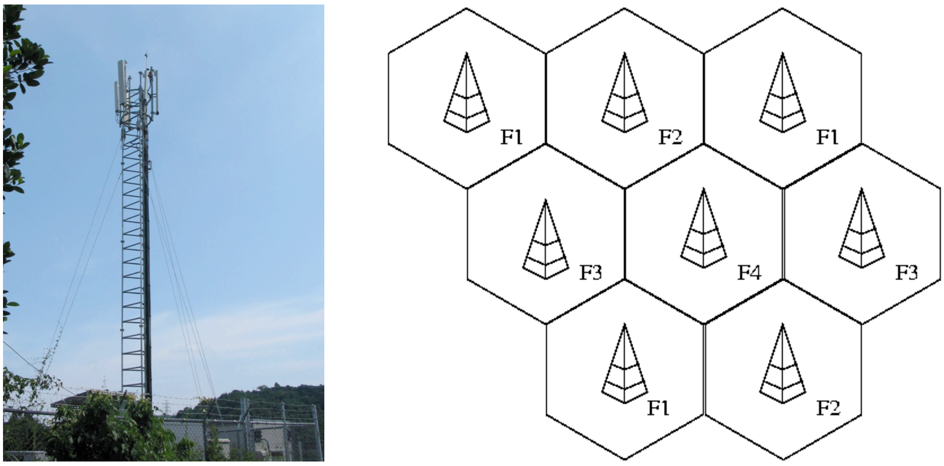

Figure 2 A typical BS and its theoretical distribution pattern (courtesy of Wikipedia)

2.3 Assumptions

A man-made environment, such as a town or a city, is the most common situation where the mobile phone system is utilized. In such an environment, because people locate in buildings of different heights and sizes, distribution of MS is not even and buildings block radio signal to some extent. If we assume that radio signal of BS behaves like light, which usually travels in a straight line and blocks by opaque objects like buildings, we can use the line-of-sight (LOS) analysis capability in GRASS to analyze radio signal coverage of BS as well. Figure 3 illustrates this idea using a digital terrain lit by 3 lights of different colors to simulate the effect of 3 BS. Because both visible light and radio waves are electromagnetic radiation, they have those common phenomena such as reflection, refraction, diffraction, etc. However, this paper does not take those phenomena into account. It simply assumes that when they hit a surface they will be absorbed completely.

Besides, a mobile phone system may not consist of cellular network of uniform-sized cells. In other words, each base station's signal strength may vary due to its antenna type, installation height, and other factors. For example, in a GSM (Global System for Mobile communications) network it may have up to four different sizes of cells in order to provide complete coverage, including indoor and outdoor areas [6]. Again, for simplicity, this paper only deals with base stations whose antenna are installed on buildings above average roof top level and thus create the macro cells in GSM's terminology. In addition, those base stations are assumed to have uniform radio signal strength and channel capacity.

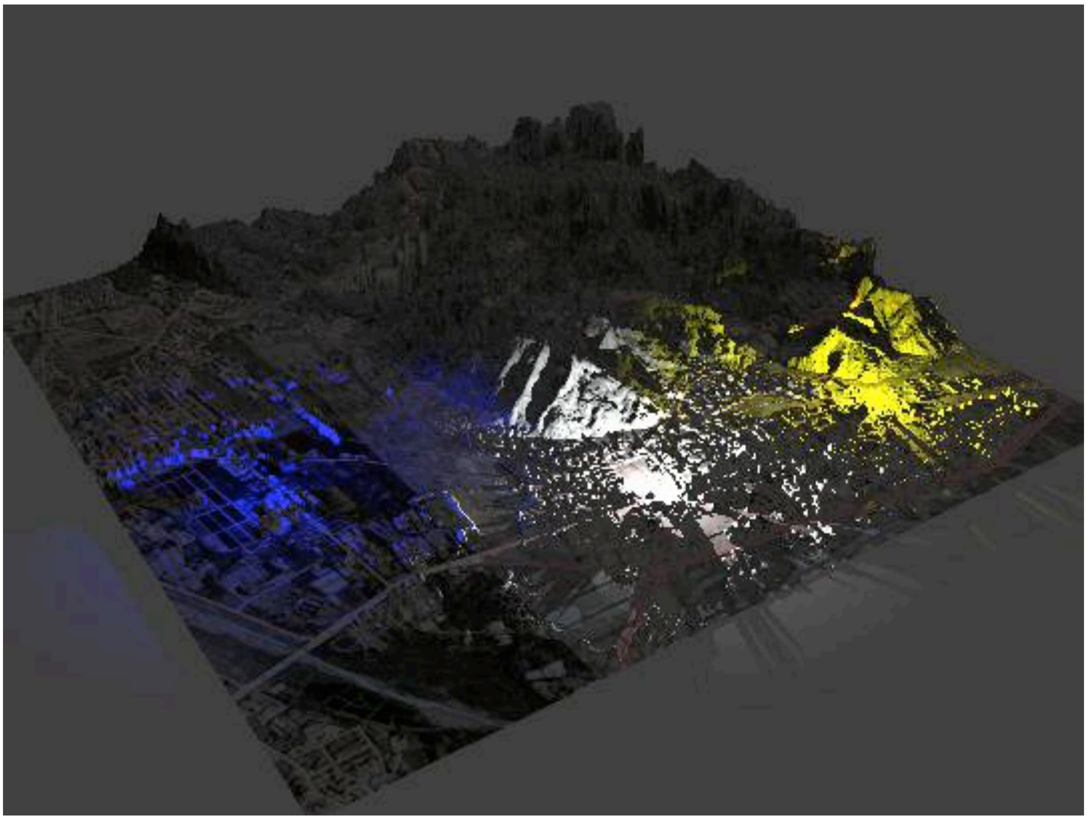

Figure 3 Using 3 virtual radial lights to visualize the effect of setting up 3 BS

2.4 Rationale of the solution

Suppose we are a mobile phone system provider, who plans to offer service to a small town for the first time. The initial task is to set up a cellular network comprising of only macro cells. The requirement of the task is to choose from a number of potential sites to set up a minimum number of BS that together will provide best radio signal coverage within the study area. This is the setting upon which the GRASS-based solution is going to be applied.

As previously mentioned, four factors, signal strength, channel capacity, terrain, and distribution of MS, involve in the siting process. Suppose signal strength is given and fixed, so we know the radius of the maximum coverage of each BS. The channel capacity and the digital terrain model (DTM) of the study area are also available. So is the map of building footprint associated with the information of the number of floors. In addition to the known locations of the potential BS sites, these are the inputs to the solution. After some map algebra operations, we can have a DTM that includes building height and a map of MS distribution, which is derived from the estimation of how many MS per unit floor area.

Since the LOS calculation is implemented as a raster module, our solution is also exclusively raster-based. As such, the development of our solution takes on a worm's-eye view-from the perspective of each cell in the raster map [4]. Now if we are at the center of a raster-cell, we can perform the following tasks.

1. Through whether or not we can "see" a particular potential BS, we know if we can possibly receive signal from that potential BS.
2. By calculating the distance, we also know whether or not we can be served by that BS's signal.

3. After we repeat the previous two tasks for all potential BS, we will get a number of qualified BS candidates as well as our preference to them based on signal strength or proximity.
4. Suppose that each BS candidate can tell us its current available channel capability. Based on the number of MS within our raster cell, we will know whether or not a BS candidate can serve all our MS demands. We will thus talk to each BS candidate in turn, from the nearest to the farthest until we find the candidate that can serve our needs.
5. Finally if we go through every possible combination of cellular networks that are formed by chosen from the potential BS sites and perform the previous four tasks for every raster cell in the study area, we can eventually find the optimal solution.

3 Implementation

3.1 Some compromises

Although the rationale described above is not difficult to understand, its implementation in GRASS may face some difficulties. First of all, in the real world the demand for a BS from a MS, i.e. where someone is going to use a mobile phone to make a call at what time for how long, is purely stochastic. Therefore it is inevitable that any implementation based on a deterministic algorithm involves certain degree of errors. This is also the case here. Secondly, because the implementation described here uses only default GRASS commands, Bash scripting capabilities, and other UNIX utilities, the additional capability, flexibility and efficiency provided by directly programming a custom GRASS module are also sacrificed.

3.2 The algorithm

The BS siting algorithm to be implemented in GRASS is summarized as follows.

1. Collect and prepare the required information as inputs, such as the DTM including buildings (the terrain map) and the map of MS distribution (the demand map).
2. Select an unprocessed BS and create the distance map of that BS through calculating the distance from the raster cell where the BS located to every raster cell in the map.
3. Create the availability mask of the BS from its distance map to block or ignore those raster cells that are outside the BS's service range.
4. Create the visibility map of the BS through the line-of-sight analysis from the BS to every raster cell that is within its service distance.
5. Add those raster cells that the BS cannot "see" from the visibility map to the availability mask to block or ignore them from further consideration.
6. Save the availability mask of the BS that indicates its visible and reachable raster cells for later use.
7. Assign those MS demands in raster cells accessible to the BS according to their likelihood of being served, i.e. their distances to the BS because closer ones get stronger signal than farther ones, until the BS reaches its capacity.
8. Go back to step 2 unless all BS have been processed.
9. Select an unprocessed set of BS combination and then create an empty assignment map.
10. Prepare the distance map of each BS so that those invisible and unreachable raster cells have extremely huge distances.
11. For each raster cell, identify the closest BS by finding the minimum distance from corresponding cells of all distance maps of the BS set, and then record that BS in the assignment map.
12. Go bask to step 9 unless all possible combinations of BS have been processed.

13. Examining the coverage or other relevant criteria of the final assignment maps of every BS combination, we can find which combination of BS provides the best service in terms of our chosen criteria. That combination can then be seen as the optimal solution.

3.3 The scripts

An exemplary GRASS application of assigning MS to twelve potential BS that is based on an implementation of the above algorithm using Bash scripts is described as follows.

3.3.1 Code listing of the "bs.test.sh" script

```
#!/bin/sh

if test "$GISBASE" = ""; then
echo "You must be in GRASS to run this program."
exit
fi

bs.dist.sh 1 125 1425
bs.dist.sh 2 525 1825
bs.dist.sh 3 575 2175
bs.dist.sh 4 525 2175
bs.dist.sh 5 675 2525
bs.dist.sh 6 625 2725
bs.dist.sh 7 675 2775
bs.dist.sh 8 1275 3425
bs.dist.sh 9 2275 3425
bs.dist.sh 10 2675 3475
bs.dist.sh 11 2225 3075
bs.dist.sh 12 2525 2275

bs.site.sh
```

As shown in the above code listing of the main script "bs.test.sh", the calculation is divided into two parts, bs.dist.sh and bs.sites.sh.

3.3.2 The "bs.dist.sh" script

Given the aforementioned four factors as input, the first part of the "bs.test.sh" script calculates radio signal coverage of each potential site if a BS is set up there, using a script called "bs.dist.sh" whose code listing is shown in appendix A1. Because terrain and buildings will block radio signal and distribution of MS is not even, the coverage of each potential site will be irregular and none is similar.

3.3.3 The "bs.site.sh" script

In combining the coverage of various potential sites, the rule is to assign a cell in the raster-based map to the nearest potential BS, which will provide strongest signal. After the coverage of all individual potential sites are calculated, the second part of the "bs.test.sh" script invokes another script called "bs.site.sh" that goes one at a time through all possible combinations of those potential sites to compute the total coverage of each combination. In this way, not only can we find the combination of potential sites that provides best signal coverage, but we can also analyze the effect of increasing the number of BS, whose return on investment may not be constant. Appendix A2 shows the code listing of the "bs.site.sh" script.

4 Verification

4.1 The site

The left side of figure 4 shows a bird's eye view of the digital terrain model looking from the northwest corner that clearly depicts the topography of the study area. The right side of figure 4 shows the locations of the twelve potential BS sites within the study area to be examined in the verification process.

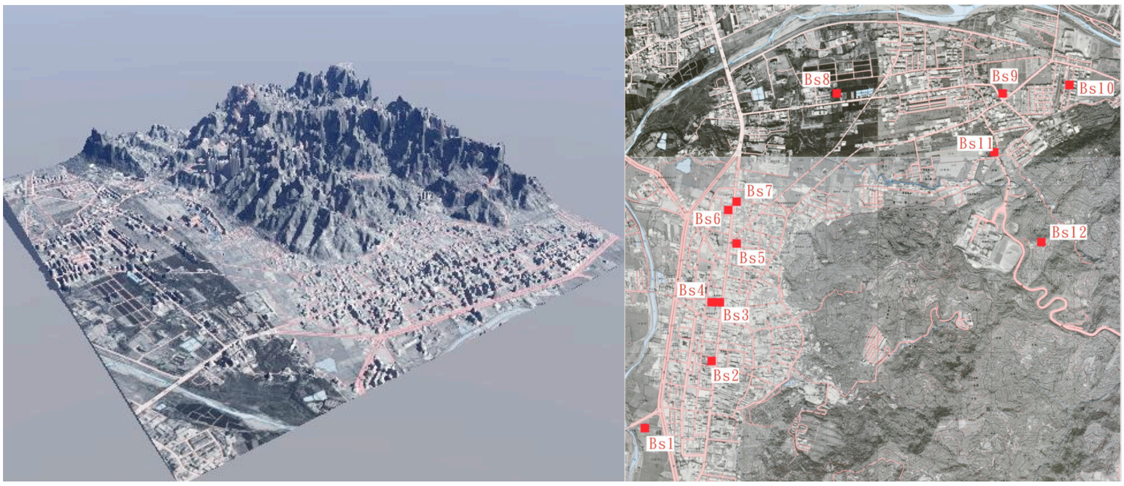

Figure 4 A digital terrain model of the study area and the potential BS sites

4.2 The results

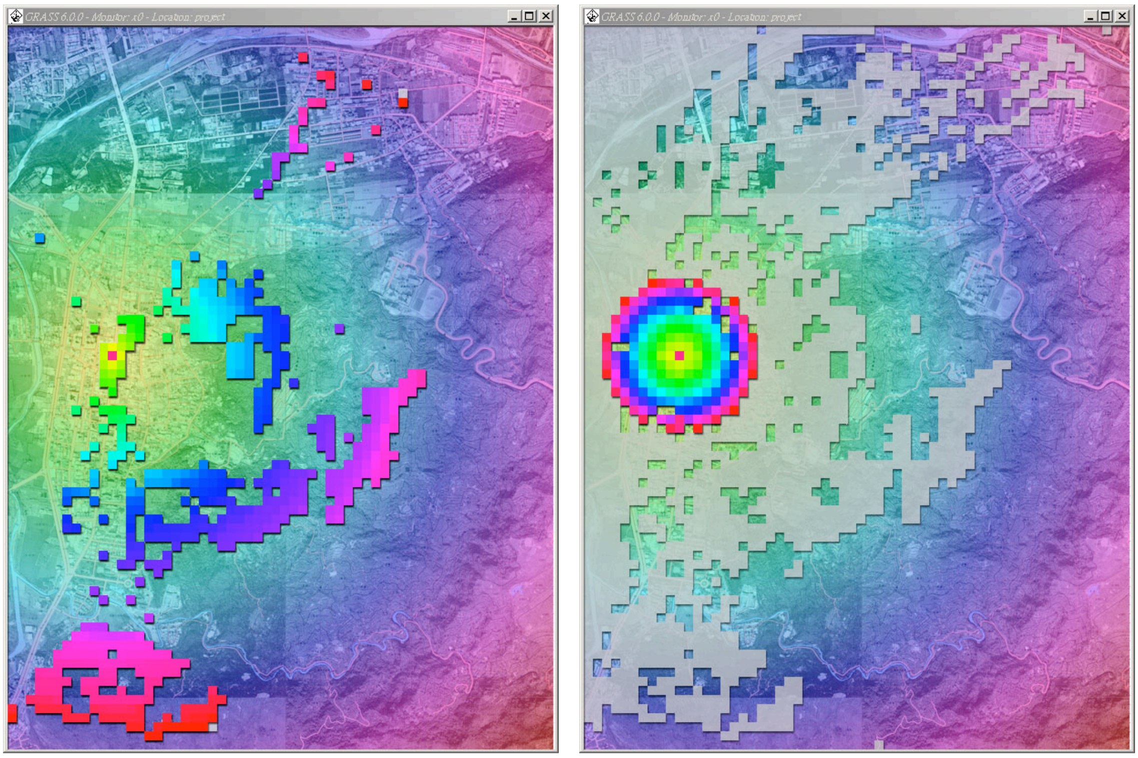

Figure 5 bs.dist.sh result for BS3 (left) and bs.dist.sh result for BS4 (right)

Figure 5 and the left side of figure 6 show three typical results of running the bs.dist.sh script. The right side of figure 6 shows one of the resulting maps of running the bs.site.sh script that illustrates the signal coverage of setting BS in all twelve potential sites.

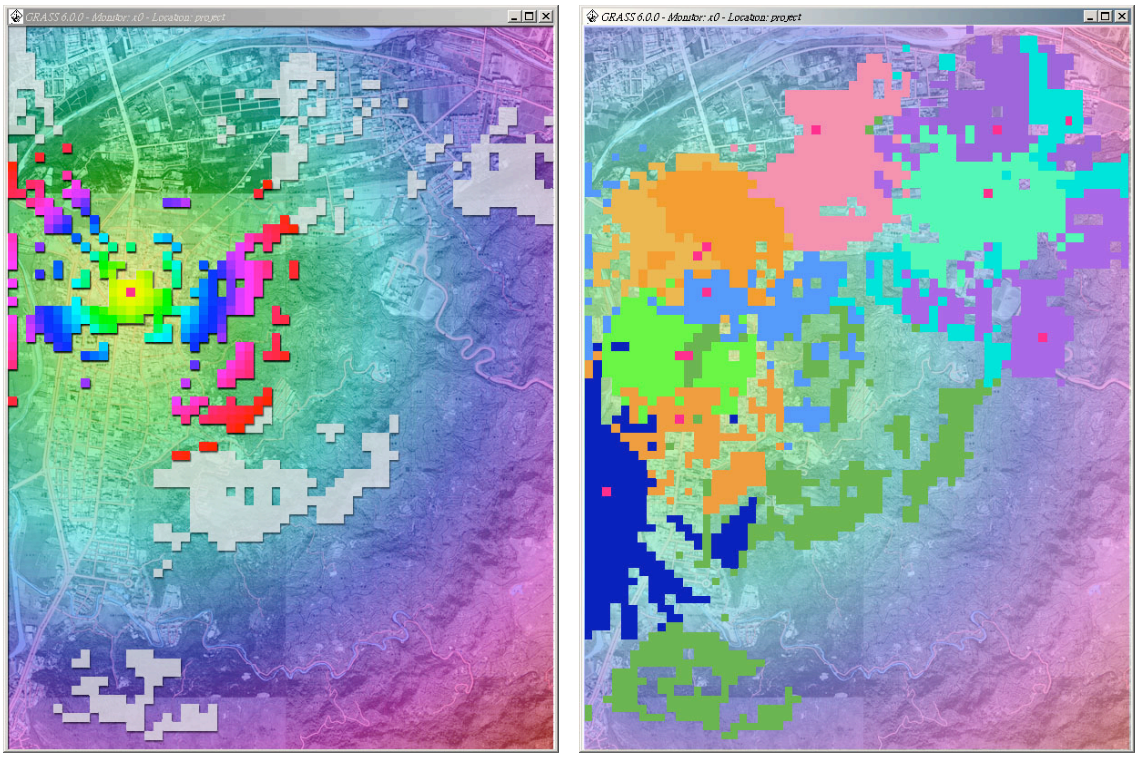

Figure 6 bs.dist.sh result for BS5 (left) and bs.site.sh result (right)

4.3 Discussion

Figure 7 shows an analysis of the absolute and relative changes of the best signal coverage as the number of BS utilized increases from 0 to 12. The analysis indicates that given the fixed cost of setting up an additional BS, the diminishing return in terms of signal coverage increment means setting up more BS beyond the break-even point is not cost effective at all.

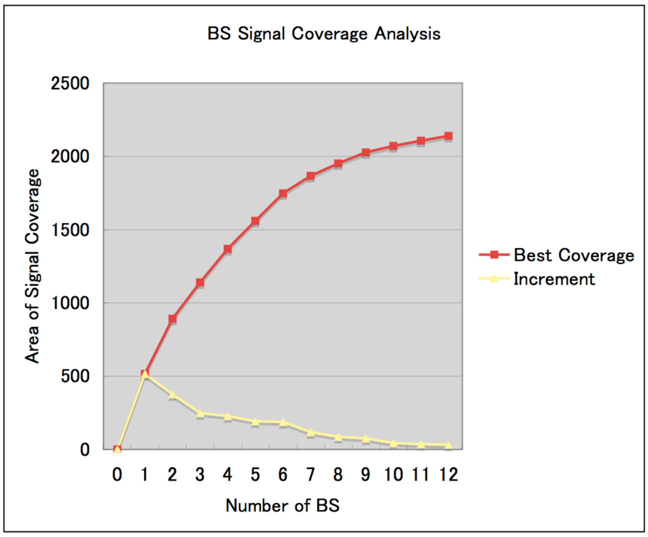

Figure 7 Signal coverage analysis of 12 potential BS sites

5. Conclusion

In summary, the BS siting problem is one type of the broader location-allocation problems. The LOS-based GRASS application described above indeed provides an intuitive approach to the BS siting problem. The verification process, however, reveals that the current bottleneck of obtaining a solution is not at the LOS computation but at the assignment of BS capacities to MS demands from near to far. This is the inherent tradeoff of devising the solution using UNIX Bash scripts rather than a lower level programming language such as C.

Further works that can be done in the short term include improving the robustness of the code so that under no circumstance will there be unused BS capacities, as well as revising the code to provide more automation and execution efficiency.

In the long run, using a stochastic simulation instead of the deterministic heuristic to reflect the true nature of people making phone calls, and replacing the simple LOS analysis with a more realistic method to model the behavior of mobile phone radio signal are two key improvements that can really make such a GRASS application shine.

References

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[8] Wikipedia contributors. Mobile phone radiation and health. *Wikipedia, The Free Encyclopedia*. August 11, 2006, 13:27 UTC. Available at: http://en.wikipedia.org/w/index.php?title=Mobile_phone_radiation_and_health&oldid=69014338. Accessed August 21, 2006.

Appendix

A1 Code Listing of the "bs.dist.sh" script

```
##### #####  ##### Global Settings #####  ##### #####
g.region n=4000 s=0 w=0 e=3000 res=50
d.erase
r.mapcalc topo="wufeng.dem"
r.mapcalc demand="wufeng_demand.dem"
height=6
maxD=5000
amount=374
#minD=100,000,000
##### #####  ##### Global Settings #####  ##### #####

##### #####  ##### For Base Station X (bs) #####  ##### #####
bs_index=$1
bs_x=$2
bs_y=$3
bs_z=`r.stats -1ng topo | awk '
        {if (($1 == x) && ($2 == y)) {z = $3}}
        END {print z}' x=$bs_x y=$bs_y`
echo "$bs_index, $bs_x, $bs_y, $bs_z"
bs_h=$height
bs_maxD=$maxD
bs_amount=$amount
bs_count_i=0
bs_count_o=0
bs_count_t=0
r.mapcalc bs="if(((x() == $bs_x) && (y() == $bs_y)), ($bs_z + $bs_h),
        null())"
r.mapcalc dist_bs_f="sqrt(((x() - $bs_x) ^ 2) + ((y() - $bs_y) ^ 2) +
        ((topo - $bs_z - $bs_h) ^ 2))"
r.mapcalc dist_bs="round(dist_bs_f)"
r.mapcalc bs_total=0
r.los input=topo output=bs_los coordinate=$bs_x,$bs_y obs_elev=$bs_h
        max_dist=$bs_maxD
r.mapcalc MASK="if((bs_los == 0), null(), 1)"   #initialize the MASK
r.mapcalc mask_1=MASK

cleanup ()
{
  g.remove rast=mask_1
  g.remove rast=mask_2
  g.remove rast=MASK
  g.remove rast=current
  g.remove rast=dist_bs_f
  r.mapcalc temp="if((bs_total == 0), null(), bs_total)"
  r.mapcalc bs_total=temp
  g.remove rast=temp
  g.remove rast=topo
  g.remove rast=demand
  eval `g.findfile element=cell file="bs_$1"`
  if [ "$file" ]
  then
    g.remove rast="bs_$1"
```

```
  fi
  g.rename rast=bs,"bs_$1"
  eval `g.findfile element=cell file="dist_bs_$1"`
  if [ "$file" ]
  then
    g.remove rast="dist_bs_$1"
  fi
  g.rename rast=dist_bs,"dist_bs_$1"
  eval `g.findfile element=cell file="bs_$1_los"`
  if [ "$file" ]
  then
    g.remove rast="bs_$1_los"
  fi
  g.rename rast=bs_los,"bs_$1_los"
  eval `g.findfile element=cell file="bs_$1_total"`
  if [ "$file" ]
  then
    g.remove rast="bs_$1_total"
  fi
  g.rename rast=bs_total,"bs_$1_total"
  d.rast "dist_bs_$1"
  d.rast -o "bs_$1_los"
  d.rast -o "bs_$1_total"
  d.rast -o "bs_$1"
}
echo "NR,BS-in,BS-out,BS-total,X-coor,Y-coor,MIN-dist" >
        bs_dist_result.txt

while [ $bs_count_t -lt $bs_amount ]
do
  R=`r.stats -1ng dist_bs | awk '
        END {print NR}'`
  if [ $R -eq 0 ]
  then
    cleanup $1
    exit
  fi

  X=`r.stats -1ng dist_bs | awk '
        BEGIN {min = 100000000}
        {if ($3 < min) {min = $3 ; x = $1}}
        END {print x}'`

  Y=`r.stats -1ng dist_bs | awk '
        BEGIN {min = 100000000}
        {if ($3 < min) {min = $3 ; y = $2}}
        END {print y}'`
  MIN=`r.stats -1ng dist_bs | awk '
        BEGIN {min = 100000000}
        {if ($3 < min) {min = $3}}
        END {print min}'`

  D=`r.stats -1ng demand | awk '
        {if (($1 == x) && ($2 == y)) {z = $3}}
        END {print z}' x=$X y=$Y`

  if [ $MIN -le $bs_maxD ]
  then
    bs_count_i=`expr $bs_count_i + $D`
    r.mapcalc current="if((x() == $X) && (y() == $Y), $bs_count_i)"
```

```
  else
    bs_count_o=`expr $bs_count_o - $D`
    r.mapcalc current="if((x() == $X) && (y() == $Y), $bs_count_o)"
  fi

  bs_count_t=`expr $bs_count_i - $bs_count_o`
  echo "$NR, $bs_count_i, $bs_count_o, $bs_count_t, $X, $Y, $MIN"
  echo "$NR, $bs_count_i, $bs_count_o, $bs_count_t, $X, $Y, $MIN" >>
        bs_dist_result.txt

  g.remove rast=MASK
  r.mapcalc temp="bs_total + current"
  r.mapcalc bs_total=temp
  r.mapcalc mask_2="if((bs_total != 0), null(), 1)"
  r.mapcalc MASK="mask_1 + mask_2"
done
cleanup $1
```

A2 Code Listing of the "bs.site.sh" script

```
bs_num=3

limit=2
for j in 2 3
do
  limit=`expr $limit \* 2`
done

r.mapcalc dist_min="min(dist_bs_1, dist_bs_2, dist_bs_3)"
d.rast dist_min
echo "Index,BS1,BS2,BS3,Coverage" > bs_site_result.txt

i=0
while [ $i -lt $limit ]
do
  q=$i
  bs_1=`expr $q % 2`
  q=`expr $q / 2`
  bs_2=`expr $q % 2`
  q=`expr $q / 2`
  bs_3=`expr $q % 2`

  if [ $bs_1 -eq 0 ]
  then
    r.mapcalc dist_bs_1m="100000000"
  else
    r.null map=bs_1_total null=0
    r.mapcalc dist_bs_1m="if((bs_1_total > 0), dist_bs_1, 100000000)"
  fi

  if [ $bs_2 -eq 0 ]
  then
    r.mapcalc dist_bs_2m="100000000"
```

```
  else
    r.null map=bs_2_total null=0
    r.mapcalc dist_bs_2m="if((bs_2_total > 0), dist_bs_2, 100000000)"
  fi

  if [ $bs_3 -eq 0 ]
  then
    r.mapcalc dist_bs_3m="100000000"
  else
    r.null map=bs_3_total null=0
    r.mapcalc dist_bs_3m="if((bs_3_total > 0), dist_bs_3, 100000000)"
  fi

  r.mapcalc dist_min_m="min(dist_bs_1m, dist_bs_2m, dist_bs_3m)"
  r.mapcalc temp="if((dist_min_m == 100000000), null(), dist_min_m)"
  r.mapcalc dist_min_m="temp"

  r.mapcalc bs_area=0
  r.mapcalc temp="if((dist_min_m == dist_bs_1m), 1, bs_area)"
  r.mapcalc bs_area="temp"
  r.mapcalc temp="if((dist_min_m == dist_bs_2m), 2, bs_area)"
  r.mapcalc bs_area="temp"
  r.mapcalc temp="if((dist_min_m == dist_bs_3m), 3, bs_area)"
  r.mapcalc bs_area="temp"

  coverage=`r.stats -1ng bs_area | awk '
        BEGIN {c = 0}
        {if ($3 != 0) {c = c + 1}}
        END {print c}'`
  r.mapcalc temp="if((bs_area == 0), null(), bs_area)"
  r.mapcalc bs_area="temp"
  g.remove rast=temp

  r.colors -q map=bs_area color=random
  d.rast -o bs_area
  d.rast -o bs_1
  d.rast -o bs_2
  d.rast -o bs_3

  echo "$i,$bs_1,$bs_2,$bs_3,$coverage" >> bs_site_result.txt
  i=`expr $i + 1`
done
```