

A MOBILE INFOSTATION SYSTEM FOR WIRELESS DATA COMMUNICATIONS

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ABSTRACT

This paper presents a new wireless system for data communications based on the “many time many where” paradigm and on the waterfilling concept, i.e., to transmit only when source and destination are close together. We associate the ideas of infostations with limited coverage at high data rates to the concept of mobility in ad hoc networks, for proposing a system with fixed and mobile infostations, well suited for messaging services. We added the concept of mobility into the infostation architecture for: 1) To increasing the capacity of the system; 2) To reduce delay in the access process, and; 3) To make information accessible simultaneously from as many points, as possible. We also evaluate some of the improvements in capacity, coverage for the benefit of the amount of information to be transmitted.

Key words: wireless communications, infostations, mobility, capacity

1. Introduction

Over the recent years we have been faced with a tremendous growth in wireless voice communications, while wireless data services have not experienced equal success. The main goal of cellular systems design has always been to provide ubiquitous coverage at some minimal quality. But the idea of having wireless connectivity "anytime, anywhere" imposes barriers to wireless data services such as low speed, high power consumption, and high cost per transmitted bit. In [6], the authors show that for wireless data to become a reality, the transmitted bits must be essentially "free", which will not yet be the case in 3G systems.

Recently, new ideas are emerging contrasting the "anytime, anywhere" paradigm, such as Infostations and ad hoc networks, both based on the waterfilling concept, i.e., to transmit only when source and destination are close together. Results obtained in these topics have provided good estimates that permit such systems to become the basis for low cost, wireless data transmission.

A new system has been proposed at WINLAB [1] consisting of isolated pockets of high bandwidth wireless connectivity called Infostations. This "many-time, many-where" paradigm is not suitable for voice or delay sensitive applications, but it is well suited for messaging services. Results based on waterfilling of channels in space, time and frequency [2 and 3], which implies that we should transmit more power when we are closer to the basestations (Infostations) are the main driving concepts for this new paradigm. The core idea of such a

discontinuous coverage system is that as a user passes by an Infostation, his/her terminal is quickly filled with information at a high data rate. This information can be email, faxes, local maps, music files and so on. As pointed out in [1], Infostations could be placed along roadways, in building entrances, at airports, and in other predictable and accessible locations and they can be seen as independent access ports to the Internet.

The idea of ad hoc wireless networks is also contrasting the ubiquitous coverage paradigm of the cellular systems. But the capacity of ad hoc wireless networks is constrained by the mutual interference of concurrent transmissions between nodes. In a fixed ad-hoc network, for example, results [12] show that the per-user throughput decreases approximately by a factor of $1/\sqrt{n}$, where n is the number of interfering users. This is a limiting result on the scalability of such networks, as the traffic rate per source-destination (S-D) pair actually goes to zero as the number of users increases. On the other hand, new results in [8], which introduce mobility into the fixed network model, show that the average throughput per S-D pair can be kept constant even as the number of nodes per unit area increases. This dramatic improvement is obtained through the exploitation of the time-variation of the user's channel due to mobility.

The performance limitation in the fixed ad-hoc model comes from the fact that long-range direct communications between users is not feasible, due to the excessive interference generated. The new idea in [8] is to split the packets of each source node to as many nodes as possible. These intermediary nodes will serve as relay nodes and whenever they get close to the final destination, they hand the packets off to the destination.

This strategy is based on the same concept of the infostation paradigm that is to transmit only when the source and destination nodes are close together. Therefore, strategies of this type incur additional delay, because packets have to be buffered until the channel becomes sufficiently strong. The results in [8] only consider applications that are delay tolerant.

Based on the results we have described above, we expect that mobility can play an equally important role in order to extend the coverage, increase capacity and reduce the delay of an Infostation system. The main goal of this work is to connect the ideas of Infostations with limited coverage at high data rates and mobility. We propose a hybrid system where some Infostations are mobile and we evaluate some of the improvements in capacity, coverage and throughput that can be achieved.

This paper is organized as follows. First we discuss the infostation paradigm and its main design issues. We then describe the proposed system, including the connectivity architecture and also the new challenges that arise when we add mobility to the system. We describe next the analytical model used and present the results of capacity, coverage and throughput gains obtained with the mobile infostations. To sum up we draw some conclusions and state future work possibilities.

2. Review of the Infostation Concept

The architecture of an Infostation system can be seen in Figure 1. The pockets of high bit rate connectivity can be seen as independent access ports to the Internet, or organized into groups with a common server (cluster controller) that is a gateway to the Internet. Associated with these locations are characteristics of user mobility patterns resulting in different scenarios [4]. The *drive-through* scenario corresponds to high-speed users that pass through the coverage area in seconds, as in a roadway; the *walk-through* scenario is characterized by slow speed

users, such as in a sidewalk or a mall; finally we have the *sit-through* scenario where stationary users, such as those in an airport or a classroom disputing access.

This system has a hierarchical architecture where each controller has information about all requests that were made in that cluster and the number of users being served at every infostation in that cluster [4]. The cluster controller can also coordinate the delivery of information to users. In some cases, as in the *drive-through* scenario, infostations communicate with each other through a radio path in order to deliver packets to the next infostation in the mobile path. The access between the infostation and cluster controller could be wired or dial-up, depending on traffic and latency [5]. The controllers could be connected to the Internet through a fixed backbone.

Let R_i be the rate between a cluster controller and the Internet, R_b the rate of each link between the cluster controller and the infostations and R_r the radio rate in the downlink, see Figure 1. As described in [4], there are different combinations between these three parameters. However, the idea of short connections at high data rates restrict the possibilities to the case where $R_r \gg R_i, R_b$. Results about the file delivery problem in [4 and 7] were obtained under the above assumption.

It is important to note that the hierarchical architecture with cluster controllers does not require any coordination between infostations in order to reuse channels, as in a cellular system.

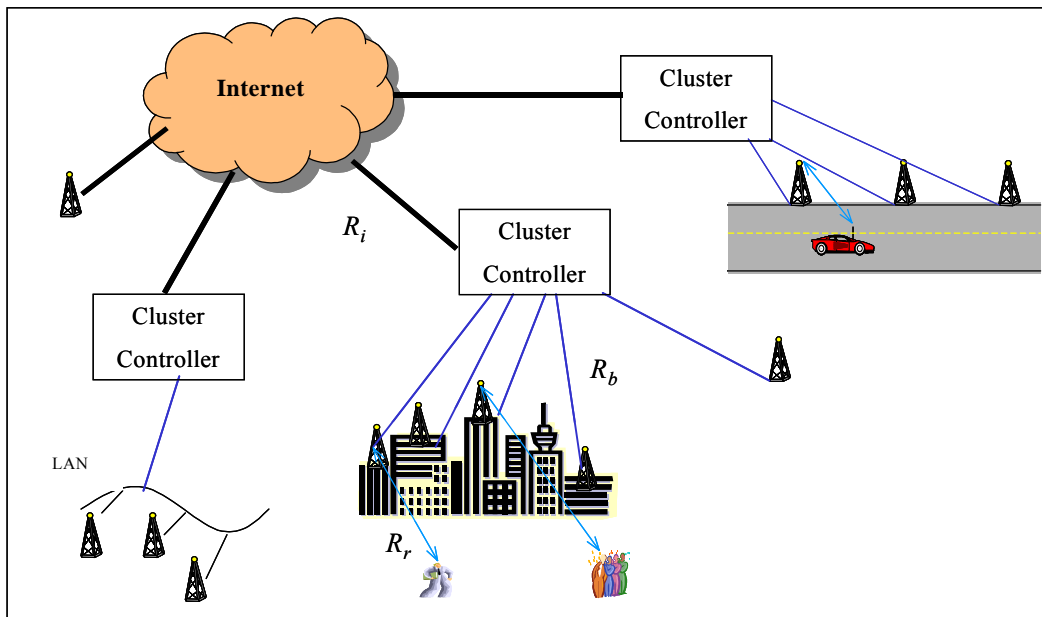


Figure 1: Infostation system architecture

Several different problems are related to an Infostation network ranging from the physical to application layers and have been studied but not yet completely solved in previous works [1, 3, 4, 7, 6, 5]. Some of the issues are: radio design, capacity, coverage, layout, multiple access, and delay in file delivery.

The major issue in the physical layer is to support transmission rate switching depending on the mobility of the terminal, the network environment, the file size to be transmitted and the

Quality of Service (QoS) constraints of the application. It is expected that the radio system from the infostation to the mobile will be able to transport variable data rates up to several megabits per second. Under the assumption that traffic is asymmetric, the communication in the uplink can be at a lower data rate. As suggested in [5], a possible approach is to use TDD transmission with simple amplitude modulated downlink and an uplink using modulated reflection.

In the MAC sub layer, the protocol will depend on the infostations scenario. In the *drive-through* there will be very few simultaneous users. On the other hand, in the *sit-through* the channel resources will have to be shared between users. The protocol has also to prioritize users depending on their mobility in a hybrid scenario.

Issues in the data link layer deal with choosing the best framing and error correction scheme to match the data link protocol to the changing properties of the transmission path. Flow control, connection management, authentication and security are issues that have also to be addressed. The WINMAC protocol was proposed in [14] to cover issues related to physical, MAC and data link layers.

Challenges in the transport layer are intermittent connections and the limited capacity to transmit acknowledgments from terminal with simple radio interfaces. An important issue is to observe how TCP and UDP would work in an infostation system.

Finally, delay constraints and the file delivery problem are the main issues in the application layer. The work that has been done in this area [4, 7] specifically tries to find delay bounds on information delivery for a variety of simple user mobility scenarios and infostations geometries.

3. A Mobile Infostation System

Related research using the idea of mobile basestations has been done in the cellular systems context. A channel allocation scheme in a system with mobile basestations has been proposed in [11] to improve the cellular system capacity. A broadband mobile cellular system called Carrucel has recently been proposed in [9]. The authors have already patented the idea of Carrucel. But it is a system designed specifically for highways, where users in their cars can connect to basestations arranged along a railway, moving in the same direction and approximately at the same speed as the traffic flows. All the wireless communications within this system use DS-CDMA within a 7 GHz frequency band part of absorption band A1 at 60 GHz and it aims to provide data rates up to 20 Mb/s with a cost per channel compared to the one for fixed networks. Moving basestations is also an interesting topic in the Military area, where networks in the battlefield have to be highly dynamic. A dynamic ad hoc network in which some nodes are moving basestations was proposed in [10], as a solution for networking in the battlefield.

In this paper we propose to apply moving basestations in different scenarios, under the infostations paradigm, which has a different approach from cellular systems. In other words, the main goal of the system we propose is not to provide ubiquitous coverage. We will add mobility into the infostation architecture to increase the capacity of the system, to reduce delay and to make information accessible from as many points, as possible. We propose to achieve this by using Mobile Infostations (MI) as intermediate relays nodes between source and destination nodes that can be mobile users, mobile users and infostations, or just infostations. The MIs will be used as access point for mobile users, as well, see Figure 2.

A Mobile Infostations system can be defined as an array of fixed and mobile Infostations providing discontinuous coverage access and high data rate transmissions. The main difference from a conventional Infostation system are the Mobile Infostations (MI) that can communicate with mobile users, with the Fixed Infostations (FI) and, eventually, with themselves. There are a variety of possible scenarios where MIs can be used including the three scenarios already defined for the infostations architecture. Initially, we can think about the *drive-through* scenario, for example, where users move in a highway. Antennas can be placed on the top of buses that have regular routes along such highways, transforming them in MIs. This will increase the coverage area for mobile users and the buses will also serve as access points for static or mobile users out of the fixed infostations coverage radius, as they go along the highway. If we think about a user or various users inside a bus (MI), we visualize the *sit-through* scenario and in this case the coverage is continuous, but users have to contend for access. The *walk-through* can also be a possible scenario, if we have slow speed users, as in a sidewalk connecting to MIs that pass close to them regularly. These scenarios are showed in Figure 2.

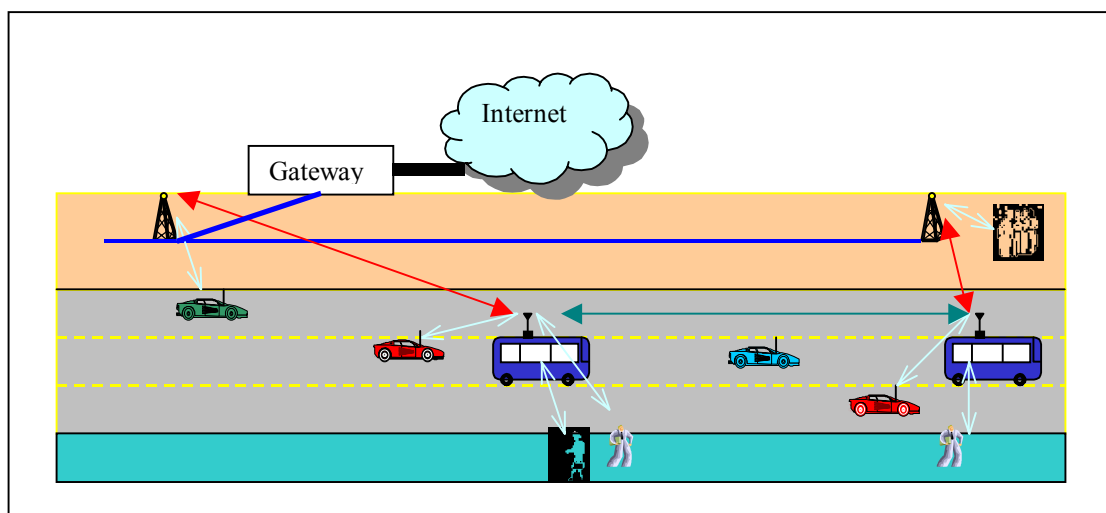


Figure 2: Example of a mobile infostation system.

Different problems related to an infostation network have been studied at WINLAB. As we propose to change the network including MIs, we have a range of new points to reexamine. Although we expect improvements, the mobile infostations increase the system's complexity as new challenges arise. In the radio design, e.g., the interference among MIs and between MIs and FIs has to be addressed. There are also new problems in multiple users access, as in a combination of the *drive* and the *sit-through* scenario, where mobile users and MI's co-located users, such as those travelling along a bus, will try to access the MI channel. Other key issues including coordination between infostations and topology management have also to be studied.

3.1. Connectivity architecture

Before a detailed study of the design issues of a mobile infostation system, we propose a connectivity model, which describes how communications take place between the network components. The communication infrastructure of the fixed infostation system was maintained, with a fixed backbone connecting FIs to gateways (cluster controllers) and connecting gateways to the Internet. FIs continue to communicate with users through a wireless channel at high data rates. But now, FIs have also to be connected to MIs through

wireless links. Finally, there are wireless connections between MIs, and between MIs and users. Figure 3 shows the connectivity model.

The data rates between the components are also showed in Figure 3. R_i , R_b and R_r have the same meaning as explained above for a fixed system. Furthermore, R_r is also the downlink data rate between MIs and users. R_f is the data rate between fixed and mobile infostations and R_m is the data rate between mobile infostations.

Here, we continue assuming that $R_r \gg R_i, R_b$ and we consider that MIs take short time connections with FIs and the maximum amount of information have to be transferred during this time. Therefore, R_f has to be a high data transmission rate, up to several megabits per second. As one of the system's goals is to use mobile infostations as relay nodes between source and destination, R_m has to be sufficiently high, to meet delay constraints to the applications, because it is closely related to the file delivery problem. An example is when a MI transfers part of the information to the next MI in the mobile user way. In this case, choosing the best R_m will depend on the relative speed between user and MI, because this speed determines the time a user takes to get the next Infostation.

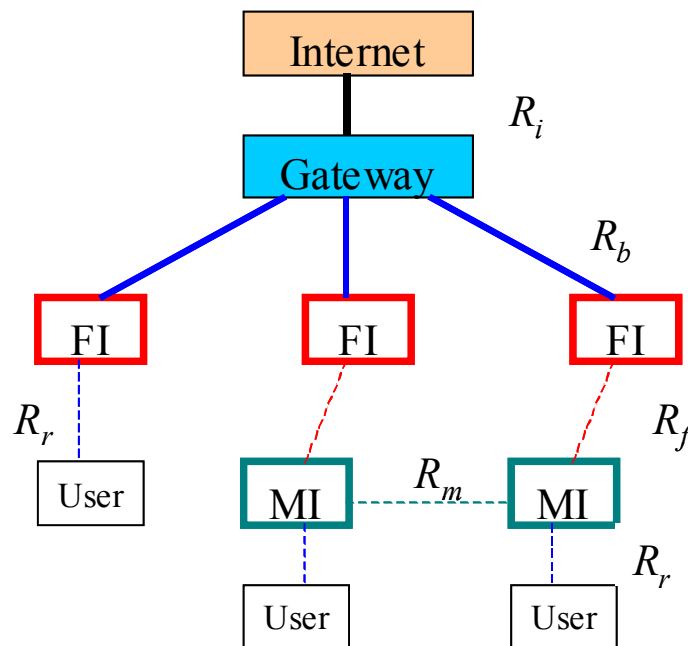


Figure 3: Connectivity model.

3.2. Mobile Infostation radio interface

As can be noted, mobile infostations are critical nodes in the system because they have to establish connections with three different nodes. This requires a lot of coordination between them, as well as a radio interface different from the fixed infostations interface.

One possibility is to think of a MI just as a mobile user that accesses the fixed infostations channels. But, differently from users, the MI may transmit at high data rates in both the uplink and downlink. The approach adopted in [9], which uses DS-CDMA spread spectrum techniques within a 5 GHz frequency band together with TDD methods for up and downlink communications is a possible choice. In this case, the MI can also see other MIs as users. In

such approach, the coordination effort can be reduced, but it has problems in multiple accesses because MIs will dispute channels with users.

A second strategy is to use different frequency bands for connection of MI to FI, MI to users and MI to MI. However, it will reduce the total frequency band available, as we have to divide it in three different parts. This strategy simplifies the analytical development, because we do not have to take into account the interference between MI and FI and MI themselves and it will be used in this paper. A more sophisticated model considering all the interferences in the system will be developed in future works.

4. Capacity and Coverage in an One-Dimensional Model

The objective here is to maximize the data rate of a mobile infostation in a one-dimensional system given a certain average power constraint. Although a one-dimensional analysis may seem too naive, it is relevant because it represents a possible real situation that is the *drive-through* scenario. A two dimensional model requires a more sophisticated analysis and it will be address in future works.

We extend the results in [5], obtained for an infostations system, including mobile infostations in a periodic highway model. We show that the optimal power control based in a reduced coverage is also the optimum for maximizing capacity in a mobile infostations network. Some results were easily obtained from the theoretic development in [5] and are detailed in this section. We also explain new results related to infostation mobility, such as, that coverage depends on the time and on the relative speed between mobile infostation and user. Finally, we estimate the gains in terms of coverage and capacity achieved when we include mobile infostation into the system. In resume, the specific goals are:

1. To evaluate capacity for a mobile user connected to a MI, which depends on both speed and moving direction;
2. To study the coverage for the mobile user considering the complete system, i.e., the user can connect to fixed and mobile infostations as he moves along the line;
3. To study how system's coverage varies for static users out of the fixed infostations coverage radios;
4. To find the maximum achievable throughput for both fixed and mobile users.

Similarly to a fixed system, a Mobile Infostation System can be designed in different ways depending on the scenario, in which it will be implanted. Therefore, we need to consider several models with different characteristics. In this work we will use as bases the model defined in [5] for a fixed infostations network and we will adapt it in order to define a new hybrid model. Performance measures like capacity and throughput will be used to compare results with the fixed infostations model in order to identify the best design strategy and the gain we have by adding the MIs.

In our model we consider fixed and mobile infostations connected through a radio link. The fixed ones are distributed periodically along an infinite line and the MIs move along this line with constant speed. We consider a single user that moves with constant speed in the same line. Fixed users are uniformly distributed along the distance.

Figure 4 shows the model that consists of Fixed Infostations (FI), with heights of h units, periodically spaced by a distance $2r$ units; and a Mobile Infostation (MI), with height of h_m units, traveling at a speed v_i . We assume $r \gg h, h_m$. At any instant, the MI position is x_i . We assume a single mobile user (MU) that travels at a constant speed v and we call x_u the position of the mobile user. Additionally, we have fixed users that we call static users (SU) at position x_s and we assume the x_i, x_u and x_s are uniformly distributed into the interval $[0, r]$. Here we define a new variable called x_r , the distance between MU and MI, i.e., $x_r = x_i - x_u$.

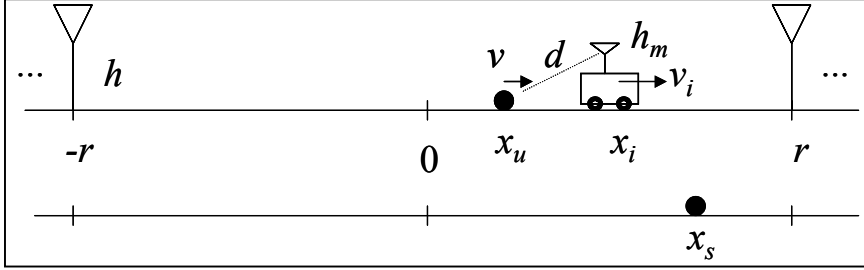


Figure 4: One-dimensional model.

We present next how we obtained the results for a Mobile Infostations system based on the development described in [5].

Considering a line-of-sight case with free space propagation and a path loss exponent $n = 2$, we calculated the Signal-to-Noise Ratio (SNR) as a function of the relative distance x_r .

$$SNR(x_r) = \frac{\alpha h_m^2}{x_r^2 + h_m^2}, \quad (1)$$

where α is the value of SNR below the antenna ($x_r = 0$).

We assume that the mobile infostation uses information about the relative position x_r , to adjust its transmitted power, $P(x_r)$ that is of the form

$$P(x_r) = \bar{P} \cdot g(x_r), \quad (2)$$

where \bar{P} is the average power, which is fixed. We call $g(x_r)$ the power gain that has a unit average.

At a given distance x_r between the MU and the MI, the Shannon capacity of an AWGN channel is given by

$$C(x_r) = \frac{1}{2} \log_2(1 + g(x_r)SNR(x_r)). \quad (3)$$

Them, we have to calculate the power gain $g(x_r)$ that maximizes the average capacity of the MI. This is an optimization problem. A similar problem is solved in [5] and we can adapt the solution to our problem, such that the optimum power gain can be expressed by

$$g(x_r) = \begin{cases} \frac{x_c^2 - x_r^2}{\alpha h_m^2}, & x_c \leq \min(x_c, r) \\ 0, & otherwise \end{cases} \quad (4)$$

where x_c is a constant that can be interpreted as a threshold distance for communication and r is the maximum value for x_r , which we consider here equal to the distance between fixed infostations, see Figure 4. We can calculate x_c using the following condition

$$\int_0^r g(x_r) \cdot \frac{1}{r} dx_r = 1, \quad (5)$$

The distance x_r can be expressed as a function of the time and the relative speed between MU and MI $v_r = v_i - v$. Writing $x_r = v_r t$, we have the following expression for the optimum power allocation as a function of the time

$$g(t) = \begin{cases} \frac{(v_r t_c)^2 - (v_r t)^2}{\alpha h_m^2}, & t \leq \min(t_c, T) \\ 0, & \text{otherwise} \end{cases}, \quad (6)$$

where t_c is a constant that can be expressed by $t_c = x_c/v_r$, which can be interpreted as the maximum time of a connection MU to MI and $T = r/v_r$.

4.1. MU -- MI connection

In this part we will evaluate coverage and capacity of a MI with a mobile user connected to it, which depends on both speed and moving direction. We do not consider fixed infostations in this case.

The optimal power gain, as a function of the relative distance between user and infostation, is presented in Figure 5a with parameters $h_m = 5$, $R = r = 1000$ and $\alpha = 30, 40$ dB. We can see that the power gain is maximum at $x_r = 0$, i.e., when the user is beneath the MI and decreases as the distance between them increases. The power gain becomes null at a threshold distance x_c .

Representing the optimum power gain and capacity as functions of the time we can evaluate situations where MU and MI move in same direction or in contrary directions. In Figure 5b, we have plotted the power allocation as a function of the time, for MI and MU moving in the same direction and in contrary directions with speeds $v_i = 60$ Km/h, $v = 80$ Km/h and parameters $h_m = 5$, $r = 1000$ and $\alpha = 30$ dB. In both cases, we assume that at the initial instant MU and MI are together at $x_i = x_u = 0$. Figure 5b shows that the coverage time can be very different depending on the relative speed. When the MU and MI move in different directions the coverage time is drastically reduced because the relative speed increases.

Figure 6a shows the "instantaneous" capacity versus time for the same example. We can see that the spectral efficiency decreases to zero as the time passes, i.e., as the MU moves away from the MI. When they move in contrary directions the capacity rapidly decreases to zero.

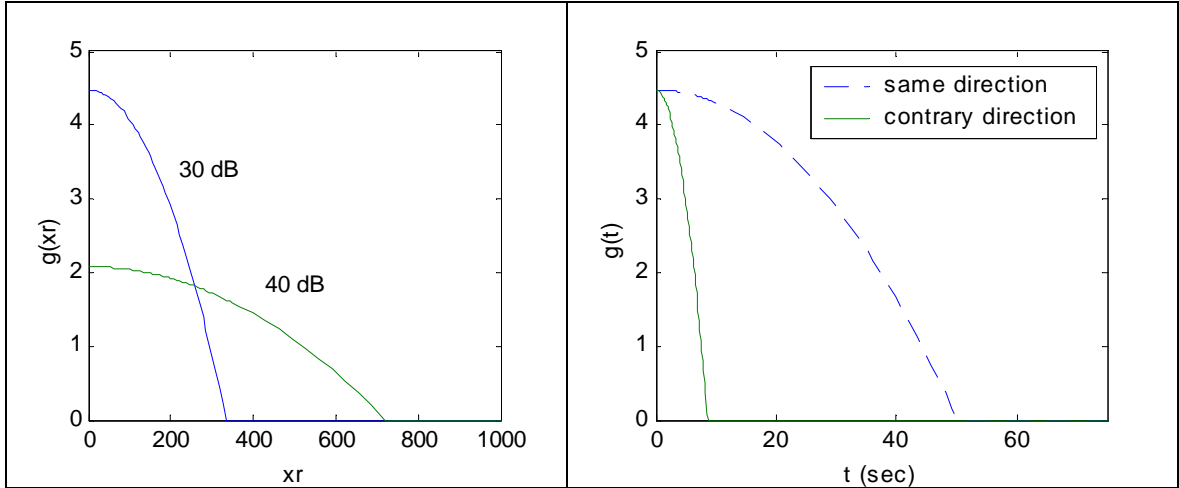


Figure 5a: Optimal power control ($h_m=5$, $r=1000$ and $\alpha=30,40$ dB). Figure 5b:

Optimal power control ($v_i=60$ Km/h, $v=80$ Km/h)

4.2. MU -- (MI and FI) connection

In this case, we consider a mobile user and a mobile infostation traveling at the same direction, and a fixed infostation at position r . Again, we assume that at the initial instant the MU and MI are together at $x_i = x_u = 0$.

In Figure 6b, we have plotted the optimal power allocation as a function of the time for both connections MU to MI and MU to FI. Here, the same equations obtained above can be used for the FI, which is represented by a MI with null speed and located at position r . The parameters used were $h=10$, $h_m=5$, $r=2000$, $v_i=60$ Km/h, $v=80$ Km/h and $\alpha=30$ dB. The MU stays connected to the MI until the threshold distance separates them and it takes a longer time than the connection of the MU to the FI. We can also observe that the coverage area of the MI does not overlap with the FI coverage area what represents a gain in coverage for the system.

The capacity as a function of the time is shown in Figure 7a, for the same parameters. We can see again the capacity gain obtained adding a mobile infostations to the system.

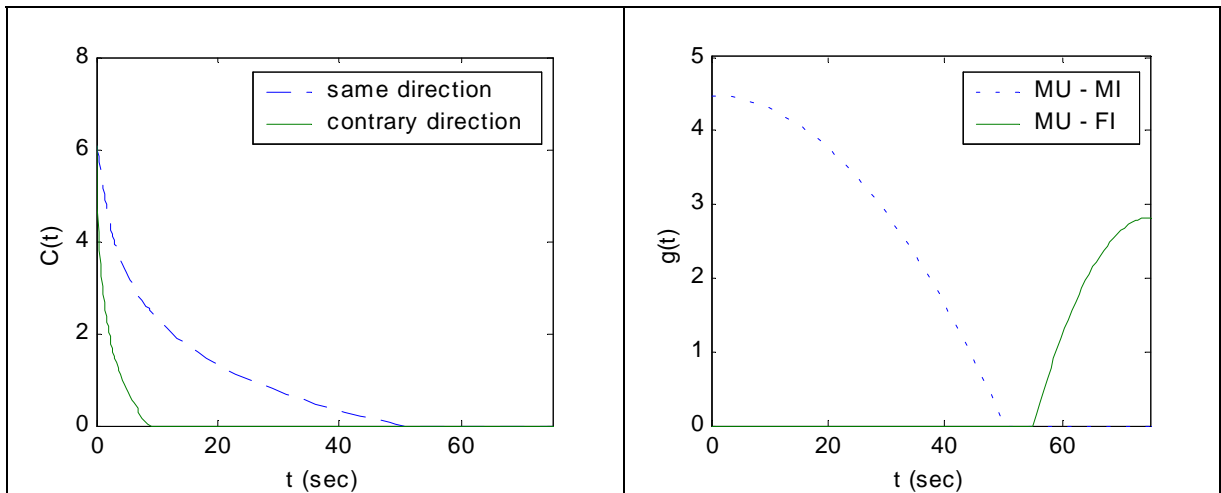


Figure 6a: Capacity as a function of the time.

Figure 6b: Optimal power allocation for mobile and fixed infostations.

4.3. SU - MI connection

This scenario can be obtained from the previous ones considering a user in a fixed position x_s , which is uniformly distributed between 0 and r . Figure 7b shows the instantaneous capacity for a MI traveling at $v_i = 60$ Km/h connected to a static user (SU) at position $x_s = 0$ and for the same MI connected to a mobile user (MU) whose speed is 80Km/h. As we can see, the only difference in the two cases is the connection time, which is longer when both antenna and user are moving at constant speeds and in same direction.

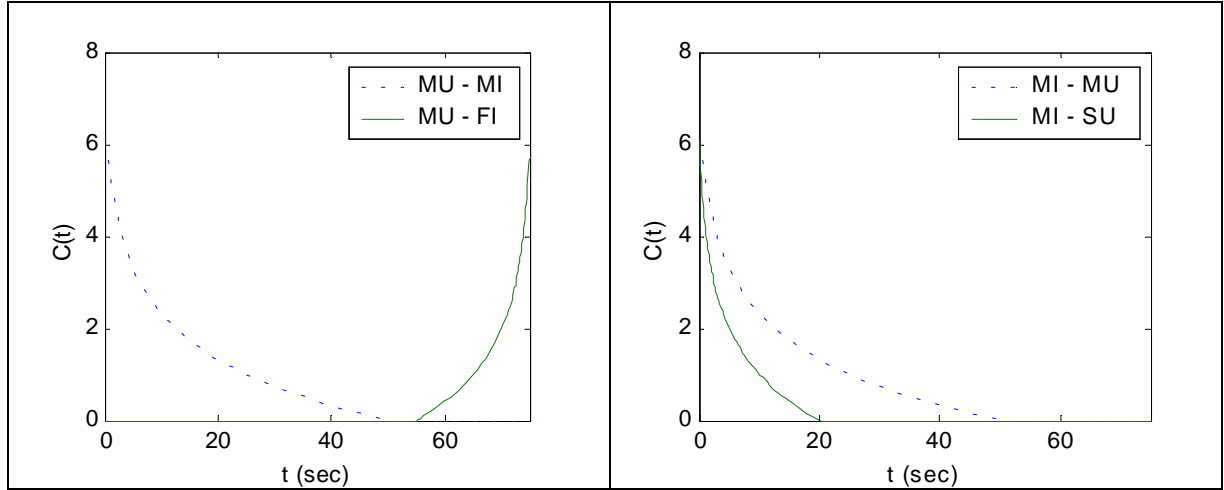


Figure 7a: Capacity as a function of the time for mobile and fixed infostations.

Figure 7b: Instantaneous capacity for Mobile and Static users.

4.4. Stochastic model

So far we have assumed that mobile infostations and users are traveling at constant speeds. Now, we change this assumption, such that the relative distance (x_r) between MI and MU is a random variable X_r , with probability density function

$$f_{X_r}(x_r) = u \cdot \exp(-ux_r), \quad (7)$$

where $1/u$ is the average distance between user and mobile infostation. In the following results we have assumed $1/u = r/2$.

Knowing $f_{X_r}(x_r)$, we can use the results described above for the periodic one-dimensional model. We will have the same power control function $g(x_r)$ because the structural form of $g(x_r)$ is independent of $f_{X_r}(x_r)$. Only the constants will have to be adjusted according to the new pdf. The condition used to find x_c is obtained by replacing the uniform pdf with $f_{X_r}(x_r)$ in equation (5). The result is

$$\int_0^{x_c} g(x_r) \cdot f_{X_r}(x_r) dx = 1. \quad (8)$$

In this case we cannot solve for an expression of x_c , but we rather have to find its value numerically.

To compare with the case where mobile user and infostation travel at constant speeds (uniform distance), we have plotted the power gain and instantaneous capacity for both cases in Figure 8a and 8b respectively. With parameters $\alpha=30\text{dB}$, $r = 1000$, $h = 10$, $h_m = 5$ we get $x_c = 335$ in the constant speeds case versus $x_c = 158$ in stochastic case.

As we observe, in the stochastic model the optimum coverage is reduced to almost a half of the value in the uniform case. At the same time, the power gain is drastically reduced what also leads to a smaller instantaneous capacity. These results show that a more accurate analysis of capacity and coverage depends on the mobility models used for both infostations and users.

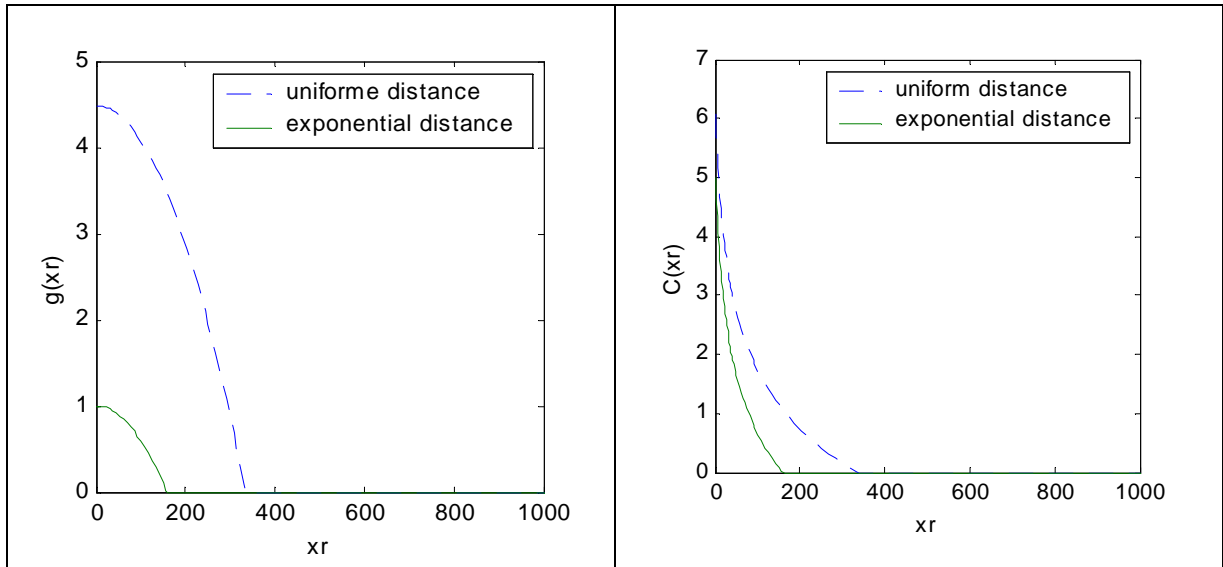


Figure 8a: Optimum power gain for the stochastic model.

Figure 8b: Instantaneous capacity for the stochastic model.

4.5. Throughput in a single mobile infostation

Depending on user's speed and on the distance to other infostations, it may take long before there is another opportunity for connection. Hence, we want to maximize the amount of information transferred while the terminal is in contact with the present mobile infostation. In this section, we evaluate the amount of information that can be transferred in a connection of a mobile user to a single MI. The design problem here is to find the optimum transmission rate and coverage distance that maximize the amount of information transferred.

The model used is shown in Figure 9. It consists of a mobile infostation and a user moving in a straight line along the x -axis at constant speeds v_i and v m/s, respectively. The user approaches the MI reaching a minimum distance d_{min} at the origin ($x=0$) before moving away. The positions of the user and the MI are denoted by x_u and x_i , respectively.

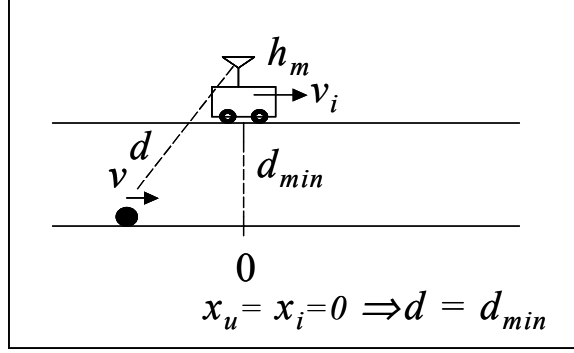


Figure 9: Single Mobile Infostation model

We assume that the infostation operates at a transmit power P_T and that the minimal signal-to-noise ratio required at the mobile receiver is γ . We further assume an AWGN channel with noise power density N_0 and propagation exponent n . If $P_R(x_u, x_i)$ is the power received and $R(x_u, x_i)$ bps the bit rate at the terminal, the SNR constraint can be written as

$$\frac{P_R(x_u, x_i)}{R(x_u, x_i)} \geq \gamma. \quad (9)$$

Hence, the bit rate is constrained by

$$R(x_u, x_i) \leq \frac{P_R(x_u, x_i)}{N_0 \gamma} = \frac{KP_T}{\gamma N_0 ((x_i, x_u)^2 + d_{\min}^2)^{n/2}} = R_{\max}(x_u, x_i) \quad (10)$$

Where K is a constant characterizing antenna gains, carrier frequency and system losses not related to propagation [13].

We use a single rate within the coverage area. In this case, at a maximum distance x_c , between user and MI, this rate will be $R_{\max}(x_c)$ bps. Therefore, we can choose the maximum coverage distance x_c meters such that we maximize the number of bits transmitted,

$$I = \max_{x_c} \frac{x_c}{v_i - v} R_{\max}(x_c) \text{ bits.} \quad (11)$$

Where $x_c/(v_i - v)$ is the time spent within coverage. By substituting equation (10) into equation (11), differentiating with respect to x_c , and setting the derivative to zero, we find the optimal coverage distance:

$$x_c = \frac{d_{\min}}{\sqrt{n-1}} \quad (12)$$

The amount of information transferred is a decreasing function of the propagation exponent n and the speeds v_i and v ,

$$I = \left[\frac{(n-1)^{n-1}}{n^n} \right] \frac{KP_T}{(v_i - v) \gamma N_0 d_{\min}^{n-1}}. \quad (13)$$

For the case of free space propagation ($n=2$), I becomes

$$I = \frac{KP_T}{2(v_i - v)\gamma N_0 d_{\min}} \quad (14)$$

One of the several engineering mechanisms used to achieve the maximum information transfer is vary the data rate by varying the symbol rate, which means the same as changing the amount of bandwidth used. In order to compare the information transferred using a single rate against a continuously changing rate, we plot in Figure 10a the maximum rate possible as a function of x_r (distance between user and MI) and the single rate used.

In the Figure 10a, $n = 2$ and the distance plotted are normalized by d_{\min} . Thus the value of x_r corresponds to $d_{\min} = 5$ meters, which is the value adopted for the MI antennas height in the previous sections. The rate in the vertical axis is also normalized by $R_{\max}(0, 0)$.

The area of the rectangle in Figure 10a is the number of bits transferred at the single rate corresponding to the height of the rectangle. Equation (12) indicates that the rectangle shown, with the boundary $x_r = 5$ is the largest rectangle that can fit under the curve. The area under the curve is the number of bits that would be received from a mobile infostation transmitting exactly $R_{\max}(x_u, x_i)$ bps at each point using a variable rate scheme. We can clearly observe the improvement obtained with a variable rate in the amount of information transferred.

To a practical implementation, we can consider that the MI could have zones of different allowable rates, what is equivalent to approximate the area under the curve in Figure 10a with a series of rectangles.

In Figure 10b we have plotted the normalized rates of a mobile user (MU) connected to a fixed infostation at the origin and connected to the mobile infostation. As we can see, the amount of information transferred is increased when the user is connected to the mobile infostation due to its longer connection time.

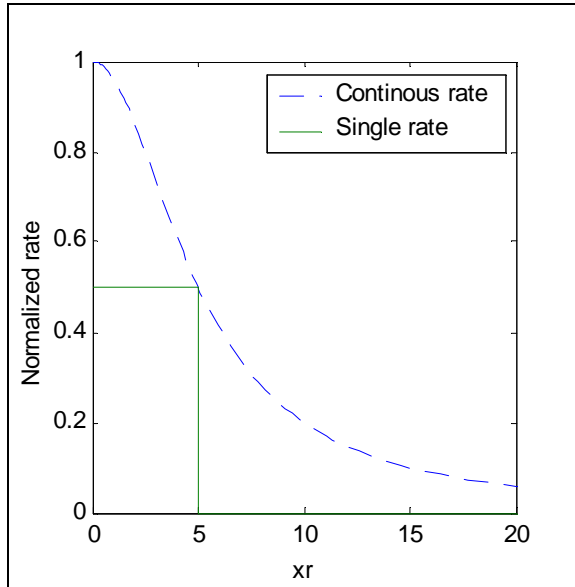


Figure 10a: Continuous and single rates.

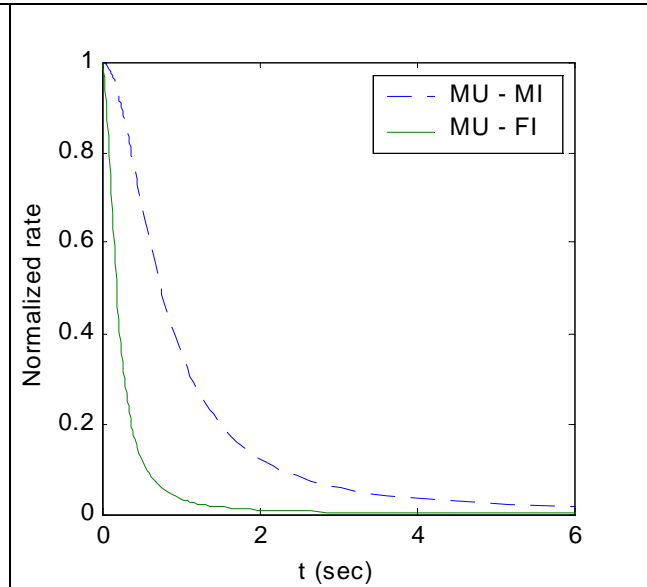


Figure 10b: Fixed and mobile connections

5. Conclusion

In this paper we have proposed a mobile infostation system in order to increase coverage, capacity and reduce delay of a fixed infostations system. The proposed system is not suitable for real time applications, and ubiquitous coverage is not our goal. The mobile infostation system is a low cost network suitable for messaging and data services that do not require ubiquitous coverage.

We have used the fact that mobility increases capacity of an ad hoc network to extend some results presented in [5], for an infostation network, by adding mobile infostations into the system. The result we have obtained supports the information-theoretic argument of the infostation paradigm that capacity is maximized with a reduced coverage. Not only for fixed but also for mobile infostation there is a cutoff distance beyond which no communication takes place.

We have calculated the optimal power control and the capacity of a Mobile Infostation as functions of time using a one-dimensional model. Results show the gain in coverage achieved when users (mobile or fixed users) out of the fixed system's coverage can be attended by a mobile infostation. It is important to note, in this case, that the connection time and capacity depend on the relative speed between user and antenna. Therefore multiple access schemes have to consider this parameter to support different classes of users.

We have also calculated the maximum amount of information that can be transferred in a single mobile infostation model. Results showed that a scheme with variable rates increases the system's performance. Finally, as we expected, we have showed that by adding mobility to infostations, the amount of information transferred can be increased in a considerably way.

In future works we will consider a two dimensional model in which fixed infostations overlay in a cellular system and we will also consider more sophisticated mobility models for mobile infostations and users as the random walk model, for example. In addition, future works will address new alternatives for MAC protocols and strategies for the file delivery problem in a Mobile Infostation System.

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