Challenges in Low-Cost Wireless Data Transmission

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Second and third generation wireless systems have been designed primarily for voice, a connection oriented, delay sensitive service requiring a specified bit rate. In contrast, data services are often connectionless, delay insensitive and have no specific bit rate requirements. These differences suggest that ubiquitous (anytime/anywhere) coverage may not be a strict requirement for wireless data networks and in fact may needlessly complicate the design. This line of thought leads directly to the notion of mobile data users intermittently connected at high bit rates. The most natural means to this end, from a classical communications perspective, is to provide isolated high bit rate "pockets" of coverage close to base station antennas through multi-level modulation and increased spectrum reuse allowed by pocket isolation. Specific issues that are relevant for such multi-tier architectures range from the physical layer extending to radio resource management and even application layers. In this article, we describe some issues for wireless data targeting the following: transceiver techniques and radio resource management.

Background

Over the past decade, the growth in wireless voice telephony has promoted the development of high quality second generation digital cellular systems. Over the same ten years, the world has waited for an equal explosion in wireless data services. Although everyone can imagine a wide variety of useful data services for mobile users, wireless data continues to languish. We believe that wireless data will most likely fail again in third generation (3G) systems as well. This is because low cost, high speed, wireless data will dictate substantially new system architectures and corresponding new approaches to the underlying communications problems.

The current 2G digital cellular systems, GSM, IS-95, and IS-136, provide good quality voice anytime anywhere. However, 2G systems provide low speed, and hence low quality, data services. The desire to support high rate data services, in addition to wireless voice telephony, is the primary factor in the development of third generation systems. The third generation is converging on wideband code division multiple access (WCDMA) technology that will provide universal coverage for 144K bps and 384K bps data services as well as limited coverage for 2M bps data [13, 14]. The choice of CDMA as the 3G technology is the result of a combination of factors: the success of the second generation IS-95 CDMA system and the desire of system operators to avoid the expense of implementing cellular frequency reuse plans. However, as a consequence of voice telephony being the dominant use, 3G systems follow 2G design principles. In particular, 3G systems will provide *anytime anywhere* coverage. While this is an appropriate design for voice services, we will see that this is not the case for data services.

The barriers to wireless data include *low speed*, *high power consumption*, and *high cost per transmitted bit.* We observe that 3G CDMA does begin to address the issue of speed but neglects the other impediments and that the research community continues to reduce the power consumption of chips. However, we will see that neither of these directions will reduce the cost per transmitted bit, the fundamental barrier to the creation of popular wireless data services.

Data services such as email, web browsing, and online shopping are at the core of the explosive growth of the wireline Internet. However, we observe that these data services only became popular with the introduction of flat-rate pricing, which encourages users to think of bits as being free. That is, rather than pay for each bit, a large file costs the same as a small file, only its delivery may be inconveniently delayed. Moreover, as DSL and cable modem technologies are deployed with these same flat-rate pricing models, free bits at high data rates are becoming increasingly common. Thus, for wireless data to become more than a niche, the transmitted bits must be essentially "free."

However, as a consequence of wireless telephony being the dominant use, the cost per bit of 3G wireless data will be high simply because the cost per bit of wireless telephony is high. Specifically, a 10 kb/s cellular voice service with an airtime charge of v cents/min roughly corresponds to a "cost per bit" of $13v$ cents/Mbyte. In current systems, airtime charges exceeding $v = 10$ cents/min are common, implying a cost of \$1.30/Mbyte. Despite improvements in receiver design, and even recognizing that some system costs are not strictly proportional to bit rate, it is hard to imagine that next generation cellular systems will offer airtime at less than one tenth of that, or 13 cents/Mbyte. We suggest that this is too high by a factor of at least 100 to allow tetherless users to regard bits as being "free." To see this, consider these scenarios in which mobile users transfer megabytes of data at 13 cents/Mbyte.

- An office worker with a digital music player downloads a two hour opera (60 Mbyte of compressed audio) for the commute to home. Cost: \$7.80
- An Amtrak passenger uses a 144 kb/s Internet access for a three hour trip from New York to Washington. With a combination of streaming video and web browsing, the average bit rate of the connection is 75 kb/s. Cost: \$13.16
- A traveler needs to synchronize his laptop with an office desktop machine before a long flight by downloading 50 Mbytes of disk file changes. Cost: \$6.50

- A tourist with a digital camera uploads 32M bytes of digital images in order to email them to friends back home. Cost: $4.16

At first glance, these costs may seem reasonable. Yet, one must keep in mind that these costs reflect the very optimistic assumption that cost per Mbyte can be reduced by a factor of ten from today's systems. Moreover, even at these prices, the costs will be high enough to discourage the carefree use that is common in the wireline Internet. Further, these scenarios describe current wireless data applications; future applications will be much more demanding.

The powerful anytime/anywhere principle is a primary factor guiding the choice of CDMA as the 3G technology; however, universal anytime/anywhere service comes at a high price. It is well known that optimal use of a collection of channels is achieved by *waterfilling* solutions in which we transmit more power on the better channels [15, chap. 8] [16, chap. 10]. Similarly, in time varying fading channels, Goldsmith [17] verifies the optimality of waterfilling in time. When we view a mobile user in a cellular system as seeing a time varying channel through variations of distance path loss, the same arguments imply that we should transmit *more* power when we are closer to the basestation! This is directly contrary to the requirements of anytime/anywhere coverage that dictates we transmit more power at greater distance from the base station. A system designed to optimize throughput, without the constraint of anytime/anywhere coverage, will have pockets of high rate coverage but large areas without any service [18]. Such a system may be unsuitable for voice telephony, but can serve as the foundation for low cost, low power, high speed wireless data systems. At WINLAB, such a system was named a network of *infostations*. As you pass by an infostation, your terminal is filled with information, whether it be email, or faxes, or perhaps local maps, just as you fill your car at a gas station.

System Models

As was noted in [18], the pockets of high bit rate connectivity provided by infostations could be spaced along roadways, in building entrances, at airports and in other predictable, accessible locations. Associated with these locations are characteristic patterns of user mobility. As depicted in Figure 1, these access options were characterized in [27] as *drive-through*, *walk-through* and *sit-through*. The basic concept of small, separated coverage areas for high-rate, low cost wireless data can lead to a variety of system architectures, services and access scenarios. They may be seen as independent access ports to the Internet, or organized into groups having a common server and access point. They may provide conventional web access or new information and entertainment services such as music, maps and newspapers. They may be accessed by stationary, or *sit-through* users, slow moving *walk-through* users, or high-speed *drive-through* users that pass through the coverage area in seconds. In this paper, we focus on the more challenging walk-through and drive-through environments. Technology developed for this context can be applied directly to the less demanding sit-through setting.

Specifically, it is instructive to re-examine how the scenarios described earlier can be implemented via walk-through or drive-through infostations.

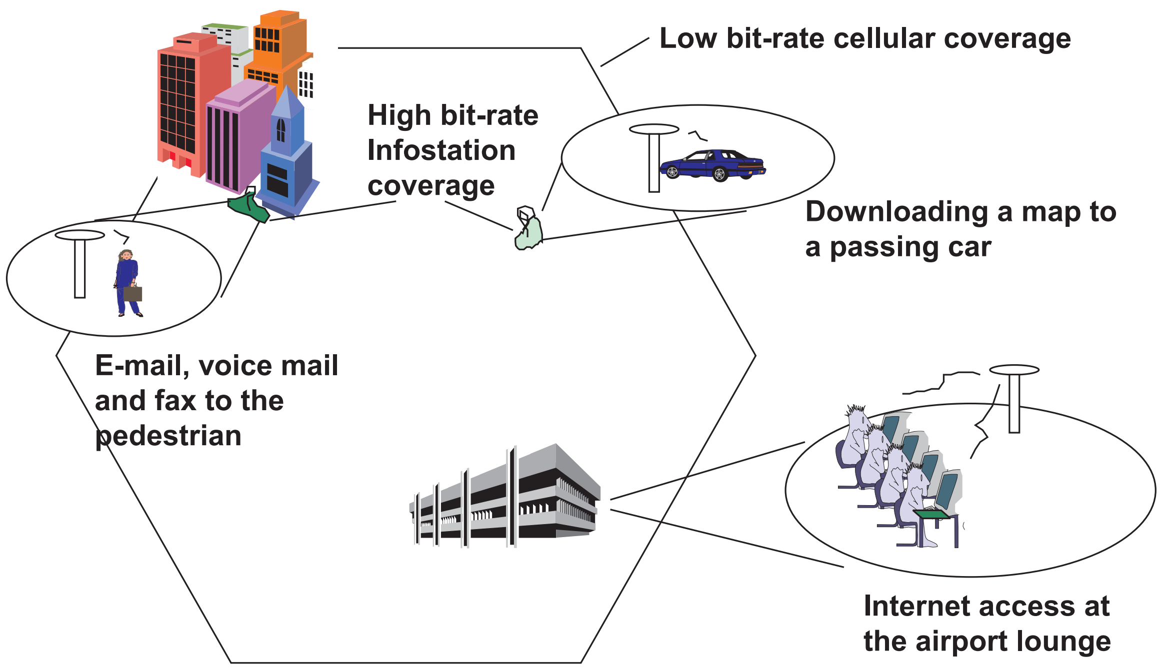


Figure 1: Examples of infostation services in isolated pockets of high bit-rate connectivity

- An infostation is located in the doorway of an office building. The office worker passes through the doorway in 2 seconds. In that time, the walker's digital music player downloads the two hour opera for the commute to home. The user would require a transfer rate of roughly 240 Mb/s.

- Infostations, each with a coverage radius of 25 m, are spaced every 500 m along an Amtrak rail line. With an Amtrak train traveling at 112 mi/hr (50 m/s), a user employing a laptop to browse the web would repeatedly see 1 second of high rate coverage followed by a 9 second interruption. If the high rate coverage offered 400 Mb/s, the user would see a Internet access system with a time average capacity of 40 Mb/s, providing a multi-access capacity for more than 40 users at 75 Kb/s.

- A laptop computer passes through an X-ray machine at the airport in 1 second. In that time, the laptop synchronizes its disk with the traveler's office machine by downloading 50 Mbytes of disk file changes at 400 Mb/s.

- While passing by a photo kiosk, a tourist with a digital camera uploads her images in one second in order to email them to friends back home. The camera data rate is 256 Mb/s.

Since these data transfers will occur over short distances, it will not be necessary to employ cellular frequency bands to make those transfers. In particular, the 5 GHz unlicensed national information infrastructure (UNII) bands [12] are intended for just such applications. In such a band, the cost of these wireless transfers need not be greater than that of wireline LAN technology. That is, over short distances, Infostations will provide the free bits that wireless data services require. Moreover, these free bits at high rates will create opportunities to deliver new wireless information services.

Achieveable Data Rates

From the above scenarios, we see that novel wireless data applications become possible when it is possible to transmit hundreds of megabits per second. The following link budget calculation verifies that such rates are indeed possible. Suppose we wish to achieve a target data rate of $C = 500$ Mb/s using the 5.25-5.35 GHz UNII band providing $B = 100$ MHz bandwidth. The Shannon formula $C = B\log_2(1 + \text{SNR})$ dictates an SNR of 15 dB. With a noise floor of $kTB = -94$ dBm, the minimum received signal level would be -79 dBm. A carrier frequency of $f = 5.3$ GHz yields a wavelength of $\lambda = c/f = 5.66$ cm, so that at a distance of $d = 50$ m, the free space path loss is $L_p = -20\log_{10}(\lambda/4\pi d) = 81$ dB. With $P_t = 50$ mW (17 dBm) transmit power, transmit and receive antenna gains of 0 dB, and losses in the receiver of $L_r = 6$ dB, we obtain a received signal level of $P_r = P_t - L_p - L_r = -70$ dBm. Thus at a distance of 50 m, we are 24 dB above the noise floor and 9 dB above the SNR required to achieve 500 Mb/s.

It is likely that this link budget calculation is optimistic. At a distance of 50 m, propagation is likely to be much more lossy than free space. The channel is likely to suffer from time varying multipath. In a UNII band, there may be interference from other uses. These impairments, particularly the unpredictable characteristics of unlicensed interference, would be deadly if we were engineering a system with universal coverage. In an infostation system, these same impairments will simply limit the coverage. An infostation providing 100 m of coverage in one location may provide only 10 m of coverage in another, and perhaps no coverage in a third location. Yet, if there is simply a sufficiency of places in which infostations can provide nontrivial coverage, a system of infostations can provide free bits at high rates to many users.

The issues discussed in this paper are based on the premise that a low cost, high speed data system will have a structure like an infostations network and we focus on network architectures and signal processing issues in this context. In the remainder of the paper, we briefly outline some system models and scenarios for infostations and outline research issues and challenges in transceiver design and radio resource management.

Research Overview

While wireless system design has received a lot of attention in 2G cellular systems and currently is being investigated for 3G systems, this new 4G system concept of isolated wireless ports requires renewed and possibly different approaches. The arguments we have made in favor of an infostations network are essentially independent of the choice of modulation. For all radios, the proximity of the infostation will result in power savings. Nonetheless, in an infostation network, CDMA is likely to be a poor choice. Specifically, the biggest advantage of CDMA is that it solves the difficult frequency reuse problem by averaging of the interference from neighboring cells [19]. However, there is a tradeoff for this advantage: CDMA systems are not particularly efficient in single cell systems. In a single cell, orthogonal channels are more efficient than CDMA both in practice as well as in theory [20–22]. In an infostation system, the frequency reuse problem becomes irrelevant since the distance separation between infostations naturally provides signal separation between users in different cells. However, such systems could still use some minimal spreading for the purposes of multipath mitigation as well as spectrum etiquette as in unlicensed bands.

Returning to the 100 MHz UNII band, we observe that with a rolloff factor of 0.25, the symbol rate will be $R_s = 100/(1 + 0.25) = 80$ Msymbol/s. In a radio channel with 10 μs delay spread, we will have intersymbol interference over 800 symbols. This suggests that we will need multiaccess protocols for the transmission of large blocks in which symbols from distinct blocks will not interfere. We note that a time division duplex structure with beacons from the infostation to mark guard times that prevent inter-block ISI is a straightforward way to do this. Our high data rate scenarios will prompt us to transmit blocks with megabits in just milliseconds. These large block sizes we will permit us to implement sophisticated block-oriented signal processing techniques that may be viewed as "too slow" (relative to the time variation of the radio channel) for traditional cellular users transmitting small packets at low rates. Further, with very high data rates, we may have the ability to use a significant fraction of each block for training symbols. For example, we can construct blocks containing multiple packets where each packet includes training sequences to allow the receiver to track channel variations.

The basic infostation communications problem is simple. When a mobile user passes an infostation, there will be a window of opportunity ranging from a fraction of a second to perhaps a few seconds in which the user will have access to a high-rate communication channel. A key task is to identify that window and transmit at an appropriate rate. The mobile must make these decisions based on measurements of a wideband unlicensed radio channel in which there is frequency selectivity and time variation in the fading as well as in the interference.

We observe from our earlier scenarios that large data transfers can occur on the downlink (infostation to mobile) as well as the uplink. However, system asymmetries are likely to dictate asymmetric solutions. For example, the infostation will likely have a permanent power source, and thus while idle can transmit beacons to allow approaching mobile users to estimate the channel accurately. Mobile terminals with battery constaints may not want to expend as much energy to facilitate channel measurements by the infostation. Further, the processing power of a mobile terminal is likely to limited. Multiple antennas are a likely enhancement to an infostation but are less likely to be used in the mobile terminal. With respect to research, uplink and downlink solutions are likely to be distinct.

In Section , we outline the fundamental signal processing challenges in an infostations environment. In Section , we examine radio resource management issues. We will see that the the radio resource management algorithms needed for infostations depend critically on measurements of radio channels and link quality. In the context of infostations, these measurements must be made in the absence of virtual circuit connections.

Transceiver Techniques

There is a basic tradeoff in having a tiered architecture and keeping the mobile unit simple. Since the preference is to use the same unit for both voice and data, it makes sense to study modulation techniques that are not only spectrum efficient, but that can also adapt to different data rate demands [29]. As an example, one can envision using BPSK for the basic voice and higher-level M-ary PSK for higher rate data. How one transitions from one to the other, as a function of the channel condition as well as the distance the mobile is from the infostation is an important issue. This problem has been addressed in the extensive literature on adaptive modulation that is being proposed for EDGE (Enhanced Data Rates for GSM Evolution) [14]. However, there has been little research emphasis on synchronization and equalization in an environment such as an infostation setting.

Most of the signal processing research in the design of 3G systems has focused on issues of equalization and interference suppression, and relatively little thought has been given to the usual assumptions made on the availability of a carrier and bit timing reference. The traditional model assumes a synchronization process of a sequential nature where the carrier reference is established first, then the bit timing is acquired followed by possible code and frame synchronization. When the synchronization process is complete, channel equalization algorithms are usually applied.

Another characteristic of current synchronization solutions is their adaptive nature. Carrier synchronization is implemented by some variation of the Phase Locked Loop (PLL), e.g., Costas loop [1], and bit timing is established through some adaptive tuning based on an error signal generated by e.g., early-late gate integrators [2]. While the adaptive implementations provide flexibility and agility to current systems, they add to the time needed for the system to tune in to the incoming signal. Synchronization typically consumes a few microseconds at the beginning of each packet, while equalization may consume much more depending on the system. Finally, code acquisition for CDMA systems may require an order of magnitude more time (several milliseconds).

This sequential model is well suited for current systems which are characterized by relatively low data rates and a connection oriented philosophy. Indeed, 1 μsec may translate to only 1/100th of a bit duration if the data rate is 10 Kbps and may therefore be negligible. But the same 1 μsec translates to 100 bits for a high speed network of 100 Mbps. This may further translate to a large percentage of the packet duration if the system uses short packets. For example, ATM networks are based on short 53 byte packets (cells), and the synchronization and equalization overhead presents a major problem in wireless ATM implementations. Recent efforts try to obviate the problem by packing together a number of cells into a longer packet at the transmitter before they are transported across the wireless channel [3].

It is clear that new DSP architectures and algorithmic solutions are needed to address those challenges and support high speed, packet based networks which may provide connectionless data services. Recent developments in software defined radio architectures [4] provide substantial flexibility and allow traditionally analog radio subsystems (frequency translation, synchronization, etc) to be implemented using signal processing algorithms. The advent of high speed and high dynamic range A/Ds and the improvements in computational hardware (FPGAs and DSP processors) allow sampling of the incoming signal at an intermediate frequency and digital processing to remove the carrier, synchronize, equalize and decode the bit stream.

When infostations operate in dense urban environments, transmissions will be subject to severe fading. Much has been published on ways to mitigate fading effects through diversity. Spatial diversity is implemented using multiple antennas either at the receiver (receive diversity) or at the transmitter (transmit diversity). Since practical considerations of cost and size limit the number of antennas at a portable handset, transmit diversity at the base station is a desirable alternative to receive diversity at the handset. Furthermore, it has also been shown that in a rich multipath environment, multiple transmit antennas are a highly efficient way to increase capacity (transmission rate), in the sense that capacity scales linearly with the number of antennas [8].

The combination of modulation schemes and error-correction coding into trellis coded modulation (TCM) provides for increased power efficiency without bandwidth expansion [5]. Recently, space-time coded modulation (STCM) has been proposed to take advantage of diversity [6, 7]. The ability of STCM to achieve transmit diversity without sacrifice in transmission rate makes STCM desirable for high data rate applications such as the infostation.

With respect to the following research problems, uplink and downlink solutions are likely to be distinct.

- **Acquisition** Since data rates are high, how one does acquisition must be revisited. A good starting point would be to try to modify the Godard technique (constant modulus algorithm) which does combined blind equalization and carrier phase recovery [9].

- **Modulation** Since these systems will transmit large blocks of data, both single-carrier and multi-carrier techniques may be viable. Orthogonal Frequency Division Multiplexing (OFDM) [10] may well be a desirable way to mitigate ISI. How OFDM, channel measurements, and rate adaptation are combined is an important question.

- **Variable Structure Equalizers** On the downlink, high data rates will require equalization at the mobile. At different distances from the infostation, there will be different demands on the equalizer. It is anticipated that at 20 meters there will almost certainly be a line-of-sight path. How this can aide the equalizer is an interesting problem. In addition, as the mobile moves away from the infostation, but is still within range for high-data rate transmission, the equalizer will have to perform better. In analogy to the proposed transition in modulation schemes, it may be useful to design equalizers whose structure "grows" or changes with distance from the infostation.

- **Precoding** The idea of a variable structure equalizer leads quite naturally into precoding procedures. To minimize the computations in the mobile, precoding can be employed. Given the high data rate, it appears worthwhile to study putting the feedback component of the equalizer in the transmitter, as one possible precoding technique.

- **Space-Time Coded Modulation** Due to the high data rates required, infostations will typically operate in frequency-selective channels with line-of-sight component. This suggests that there is a need to investigate the design and performance of performance of STCM in frequency-selective channels with Ricean or Nakagami fading models. While powerful error-correction coding like turbo-codes [11] can be used in conjunction with spatial diversity techniques, the feasibility of these techniques is an issue to be determined for infostations. While it may seem that the short-term nature of communications makes the delay incurred by turbo-coding unreasonable for use in this setting, block oriented processing may alleviate such concerns.

- **Interference Cancellation at the Handset** In infostation settings, as pointed out earlier, the high data rate communications will typically be on the downlink. Further, such communication may be primarily interfered with by one or two dominant users. It is extremely important to investigate receiver techniques that can be used at the handset to mitigate unknown interferers. From this perspective, blind adaptive multiuser detection schemes [30–32] may be extremely relevant for use at the handset. However, to reduce complexity of the receiver at the handset, it may be necessary to consider reduced order versions of these detectors. Further, in the presence of a few dominant interferers, blind adaptive nonlinear receivers may be very attractive. Preliminary work on such schemes has been outlined in [33,34]. Interference cancellation at the handset has also been considered in the context of TDMA systems in [35].

- **Packet Detection** When users are highly mobile and infostation coverage areas are small, connection oriented service may not be possible. However, a CDMA access strategy may be used to suppress interference from other systems, or perhaps from an overlay voice wide area cellular voice system. In this case, we will need to examine packet DS-CDMA systems with a connectionless architecture where no dedicated connection is kept between users and the system. In this case, a receiver will need to acquire and detect individual packet transmissions. Preliminary work in this area has been described in [36, 37] where users have to access the system using the same signature sequence and have to be acquired each time they need to send packets. Due to the asynchronous nature of the system, multiple users can be accommodated even when a single signature is available. However, even under optimistic assumptions, the capacity of such a system is less than that of G orthogonal ALOHA channels that can be accommodated in the same bandwidth of this CDMA system with processing gain G. Much additional work needs to be done in this area.

Radio Resource Management

The deployment of radio resources has received a great deal of attention in the context of time division [38, 39], code division [40–47] and hybrid systems [48–51]. In this section, we concentrate on the radio resource issues unique to the infostation. We start by

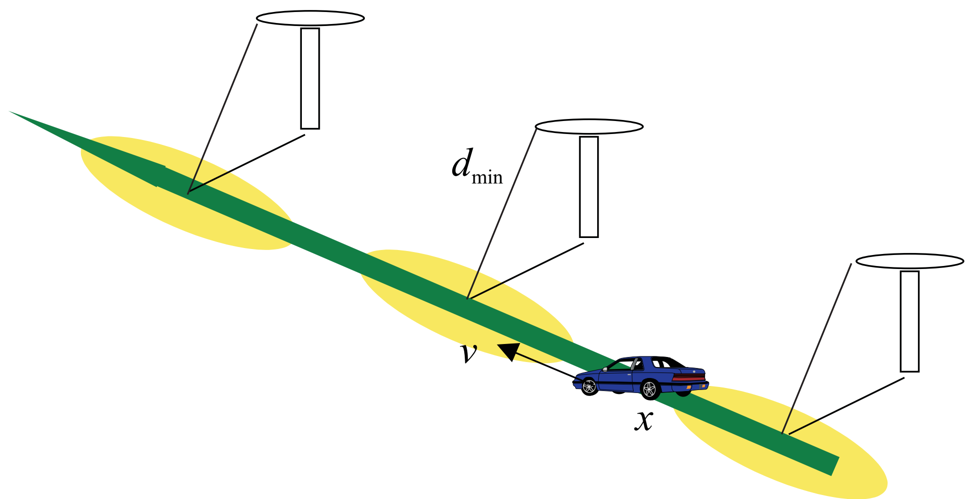


Figure 2: The multiple infostation model.

describing the optimization of coverage and capacity. Subsequently, we investigate issues related to shared access in multiple user settings. With the exception of the sit-through scenario, we believe that as a result of small infostation cell sizes, multiple terminals in the coverage area of an infostation will not be common. Moreover, in highly mobile environments in which a terminal can offer only a few packets to an infostation, only simple Aloha-like random access will be possible. Thus, our emphasis in radio resource management will be from the perspective of a few mobile terminals optimizing their communication resources. We motivate the relevant research problems with the simplest physical models.

In this section, we describe resource allocation algorithms that require several measurement tasks. These include channel estimation, bit detection, and various forms of link quality estimation. In the context of the potentially short coverage time provided by an infostation, these tasks represent signal processing challenges. Signal-to-Interference ratio (SIR) estimation algorithms using subspace techniques have been considered for both TDMA [52] and CDMA [53] systems. There is a need for further research along these lines where the primary considerations should be speed of estimation and reduction in complexity of algorithms.

We now examine how a terminal optimizes its transmissions depending on how frequently an infostation is encountered. This model assumes we have an infinite number of infostations regularly distributed, with the same minimum distance $d_{\min}$ to the terminal's trajectory, and with distance between infostations equal to $2r$ meters. Figure 2 shows the plane that contains the terminal's trajectory and the infostations' antennas. As the model is periodic, we can just consider a single period, say from $x = 0$ to $x = r$, and we will assume, as before, that we have an infostation at point $x = 0$. Given that the velocity of the terminal is constant, the position of the terminal at an arbitrary instant in time has a uniform PDF $\pi(x)$ over $[0, r]$. In the following, we consider only the propagation exponent $\alpha = 2$.

The total amount of information transferred over the interval $[0, r]$ depends on the velocity of the terminal and the number of infostations considered. To avoid this dependency, we will work in this case with bit rates, finding the maximum average bit rate, that is, the average capacity.

If a user at position x has an AWGN channel with signal to noise ratio $\mathrm{SNR}(x)$, the capacity at position x is

$$C(x) = \frac{1}{2}\log_2(1 + \mathrm{SNR}(x)). \tag{1}$$

Each time a terminal passes an infostation, a renewal occurs. Following the approach of [17], the average capacity over time is

$$C \triangleq \int_0^r C(x)\,\pi(x)\,dx. \tag{2}$$

Two cases are considered. First, we assume that the infostation uses perfect and immediate knowledge of the terminal's position to vary the transmitted power in order to maximize the capacity C. Second, we assume a simpler transmitter that can be either on at a constant power or otherwise off. Both cases are assumed to fulfill an average power constraint. If we can vary the transmitted power, the power policy to maximize the average capacity can be shown to be

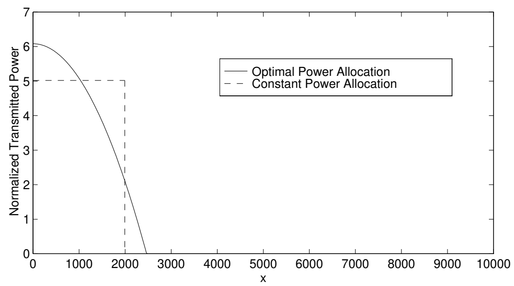
$$P(x) = \begin{cases} K(x_c^2 - x^2) & \text{for } x \le \min(x_c, r), \\ 0 & \text{otherwise,} \end{cases} \tag{3}$$

where K and x_c depend on the average power constraint. This power policy may seem somewhat surprising in that more power is allocated when the terminal is close to the infostation rather than far away. The rationale behind this fact is that the power is saved for the epochs when the channel conditions are favorable. Beyond a certain threshold distance x_c, the transmitter is simply shut off. Thus, we see that optimizing channel capacity is consistent with the infostations concept of restricted coverage areas. The expression for the average capacity is

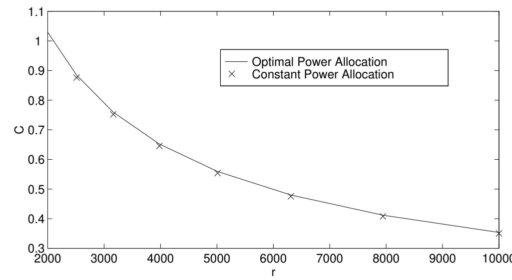
$$C = \frac{x_c}{r\ln 2} - \frac{d_{\min}}{r\ln 2}\arctan\left(\frac{x_c}{d_{\min}}\right). \tag{4}$$

In the second case, when we cannot vary the transmitted power, the best strategy is to shut off the transmitter beyond a certain threshold distance x'_c, and between 0 and x'_c use power $(r/x'_c)\bar{P}$, where $\bar{P}$ is the average power. The value x'_c can be evaluated numerically to maximize the average capacity.

Figure 3(a) shows an example with the two possibilities for transmitted power. In general, the value x'_c is less than the value x_c, i.e., the more sophisticated power control affords a larger coverage radius. Figure 3(b) shows the average capacity for the optimal case (variable power) and for the constant power case, as a function of r, the separation between infostations. In this case, we see that the average capacity achieved by the two



(a) Optimal and constant power allocations for $r = 10$ km and $d_{\min} = 10$ m, normalized by the average power $\bar{P}$.



(b) Capacity as a function of r for optimal and for constant power allocations.

Figure 3: A comparison of optimal and constant allocations. Under a constant power policy, (a) the cutoff distance is less but (b) the difference in capacity is insignificant

schemes is similar. Note that for either scheme, achieving rates close to the average capacity will require adaptive rate modulation. The bottom line here is that the average capacity is not so sensitive to the shape of the power control used as it is to the fact of saving the power for the epochs when the channel is good, that is, to the existence of a certain threshold distance for communication. Equivalent analysis for BPSK modulation using average cutoff rates yields similar results, with a loss of efficiency with respect to capacity but still quite insensitive to the power policy used. The threshold distances are somewhat larger. Therefore, using a simple power control seems as effective in terms of the amount of information transferred but the tradeoff is the larger coverage that a sophisticated power control scheme allows.

With respect to radio resource management for infostations, the following technical challenges need to be addressed.

- **Coverage and Capacity** The design objectives of an infostations network are vastly different from those of a second or third generation wireless voice system. Specifically, for wireless voice, the primary objective is to maximize coverage by minimizing the outage probability, i.e., the probability that a terminal in a random location does not obtain acceptable link quality. In an infostations network, the goal is to maximize the system capacity, as measured by the average rate at which packets can be transmitted to mobile users. We also observe that the design resources are likely to differ. In a wireless voice network, the optimization of coverage is built on cooperation and coordination among base stations. For a collection of independent public access infostations, there will not be any coordination. For a cellular system supplement, the large number of infostations in a wide area deployment is likely to preclude a centralized design to optimize coverage. In this context, distributed algorithms in which each infostation uses local measurements to adapt the size and possibly shape of its cell. It is of interest to determine if such a distributed approach results in an infostations system with high capacity. Lastly, we have shown that it is relatively simple to optimize the system in the context of a simple linear geography, AWGN channels with only distance based attenuation, and perfect channel measurements. In practice, however, we will have infostation networks on arbitrary geographies, fading channels, and imperfect measurements derived from radio signals.

- **Adaptive cell sizing** We have observed that for an individual mobile terminal, there exists an optimal coverage size to maximize its average packet rate. Similarly, an infostation can optimize its cell size to maximize its average packet delivery rate. A smaller cell size will decrease the time a mobile terminal spends in the cell and thus decrease the number of mobile terminals in the cell. However, a smaller cell will permit higher bit transmission rates. In queueing terms, reducing the cell size decreases the offered load but increases the service rate. An interesting design approach would be for an infostation to use offered load statistics to adapt its cell size. Of course, one infostation adjusting its cell size may change the offered load seen by nearby infostations, resulting in further adaptation. It is interesting to study the convergence properties and efficiency of such distributed cell size adaptation algorithms.

- **Adaptive cell shaping** With the advantage of an antenna array, cell sizing can be extended to cell shaping. Although the transmission of a just a few packets is likely to preclude adaptive beam forming for a specific mobile, over many mobile calls, the infostation would be able to learn statistical properties of the terminal locations in order to optimize the shape of its coverage area. For example, an infostation at the side of a road would create beams that extend down the road. This is one example of the general problem in which an infostation optimizes its coverage area in order to maximize its average rate of packet delivery. Just as in the case of adaptive cell sizing, this adaptation by one infostation would result in subsequent adjustments by others. It is an open question whether an infostation system will converge to a desirable coverage pattern. Note that an implementation of cell shaping must be closely coupled to the physical layer issues in Section

- **Pricing for Improving System Efficiency** Recently, there has been considerable research in the area of engineering and economics of telecommunication networks [54–60] where service provisioning is based on the level of satisfaction (or revenue) that a particular service yields to the network. While the investigations for wireline networks is still in a preliminary stage, we believe it would be prudent to anticipate such needs for future wireless networks as well. There is a need for exploring theoretical approaches of engineering such wireless systems taking into account the economic aspects. Particular questions that need answering are in regard to what economic and cost models have to be formulated that would reflect levels of satisfaction for wireless networks. While wireless resource allocation considered in the literature (for e.g. [41, 42, 45, 51, 61–67] is based on traffic engineering (i.e., the guaranteeing of QoS requirements according to the characteristics of traffic), it is necessary to investigate the general level of satisfaction that the user (and network) derives in making these guarantees available. In an infostations setting with multiple users, it is useful to consider such an economic approach for determining optimum operating points that benefit the users and the network as a whole. Specific issues that need to be considered include non-cooperative strategies based on power and rate optimization, utility maximization under delay constraints, information theoretic notions of utility and corresponding games, and dynamic pricing under energy-constrained transmission. Preliminary work on this approach has primarily focussed on distributed power and rate control strategies [68–71] in the context of microeconomics, where pricing transmit power has been shown to increase system efficiency. These concepts need to be further explored for radio resource management strategies such as call admission, channel allocation as well as handoffs.

Summary

The evolution of 2G and 3G wireless systems seems to fall short of the promise of affordable high date rate services and applications. We have presented infostations as a system concept that can provide isolated pockets of high bandwidth connectivity for future data and messaging services. Infostations that create isolated areas of high bandwidth radio transmission represent a new approach to delivering information to wireless terminals. One may consider cases in which infostations would be integrated into, or coordinated with a ubiquitous, low bit rate service such as cellular, or with paging or even wireline services. In addition to the configurations in which the infostations are independent access ports to the internet, geographic clusters of infostations could act as isolated networks for a variety of applications. We envision that the very high bit rates of infostations will create opportunities to deliver new wireless information services, and that a single set of equipment and protocols will be able to provide different applications in different environments.

The intermittent connectivity available to mobile terminals using a network of infostations raises new issues in protocol design at several layers. In this paper, we have outlined the challenges in transceiver design and radio resource management in the context of an infostation setting. While transceiver design and radio resource management in ubiquitous cellular systems has received a lot of attention, this new system concept of isolated wireless ports requires renewed and possibly different approaches. Key issues that arise in designing infostations include novel signal processing approaches at the base station and the handset, multiple access technologies, coverage and layout, guarantee of achievable payloads, and algorithms for power control and handoffs.

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