Mine, Mine, Mine: Information Theory, Infostation Networks, and Resource Sharing

Ana Lúcia Iacono and Christopher Rose
WINLAB - Rutgers, The State University of New Jersey
73 Brett Road – Piscataway NJ 08854-8060
email:{alap,crose}@winlab.rutgers.edu

Abstract: The Infostations wireless data network architecture features discontinuous coverage and ultra-high radio rates for burst transfers of information between base and mobile. It has been shown previously that the infostations architecture can greatly increase the capacity of wireless data systems at the expense of increased delivery delay. In this work we explicitly consider the multiple access issue on both the uplink and downlink – to and from an infostation respectively – and sharing of fixed network links for transporting information to and from infostations. We find that in order to maximize throughput, an infostation radio link should not be shared among users. Furthermore, this *sole use* paradigm is echoed in the fixed network which transports information to and from infostations. In order to minimize average delay the fixed link to any given infostation should serve users sequentially, as opposed to in a shared manner.

I. Introduction

Over the past 10 years, wireless voice communication has grown from a rarity to a necessity. In contrast, wireless data services at rates and price sufficient to generate equal excitement remain elusive. In response, the wireless industry has proposed third generation systems with rates in the hundreds of kilobit per second range. However, the dominant traffic on such systems will probably be voice at least initially, and unless normal voice communications becomes essentially free, wireless data will never be inexpensive when provided using a cellular architecture [1–3].

This conundrum causes us to re-examine the cellular paradigm. Specifically, cellular wireless was built to carry voice traffic for people accustomed to the reliability and ubiquity of fixed telephone service. Thus, the goal of the cellular industry was coverage anytime and anywhere at some minimum quality of service. However, since data can often tolerate delay, it becomes possible to consider *convenient* access as opposed to continuous and ubiquitous access. That is, users need not necessarily be served simultaneously and users might be able to go relatively long periods without any coverage at all if the *aggregate* data rate is sufficiently high. We call the implied notion of discontinuous and intermittent high rate coverage *infostations*.

The details of the infostations concept derives simply from the notion that for a given transmit power, the closer a user is to the base station, the better the signal to noise ratio and thus the higher the potential data rate. Furthermore, if users are mobile, then users with bad channels (far away) might be able to defer transmission until their channel quality is better (closer to the base) and transmit at much higher data rates. Formal statement of the problem [4, 5] results in a "temporal waterfilling" transmission schedule which, assuming ergodic channels, maximizes the aggregate data rate [6]. This result is one of the prime motivations for the infostations paradigm.

Several different problems related to an infostation network have been studied previously [2–5, 7–15]. In this paper we explicitly consider the multiple access (MAC) issue over the air and over the shared fixed links which transport information to and from infostations. We first discuss the single infostation/multiple user case and find that the radio link should (almost) never be shared among users simultaneously. We then discuss the multiple infostations/multiple user case for fixed network transport and again find that links to infostations should (almost) never be shared, though the definition of simultaneity is a bit different. We conclude with a summary of results.

II. One Infostation, Multiple Users

We know an infostation network should consist of small discontinuous high-speed coverage areas [3–5]. However, we will show that only one user should be served at a given time – even when multiple users are nominally in coverage. Formal proofs of this contention are provided for two-user systems. However, with minor modification, the results apply to systems of many users. This *sole use* is an interesting property of infostation systems and may provide simplified control algorithms for the air interface.

A. The Downlink

Let two potential users have gains g_1 and g_2 over the same channel to an infostation. The highest aggregate data rate is achieved when the user with the best channel (largest g_i) is served exclusively. This result derives from the capacity of a broadcast channel [16] where the maximum data rates to users 1 and 2 respectively are

$$R_1 \leq W \log\left(\frac{\alpha P g_1}{W N_0} + 1\right) \quad (1)$$

and

$$R_2 \leq W \log\left(\frac{(1-\alpha) P g_2}{W N_0 + \alpha P g_1} + 1\right) \quad (2)$$

The parameter α ($0 \leq \alpha \leq 1$) denotes the fraction of broadcast power P devoted to user 1. W is the available bandwidth and N_0 is the (white) background noise.

Maximizing $R_1 + R_2$ in α results in $\alpha = 1$ if $g_1 > g_2$ and $\alpha = 0$ if $g_1 < g_2$. Thus, aggregate capacity on the downlink is always decreased if the broadcast is shared. This basic *sole use* result can be easily extended to the case of independent ergodic time-varying stochastic gains $g_i(t)$ and associated instantaneous powers $p_i(t)$ by application of results from [6] for fading channels. Equally simple is its extention to multiple users.

B. The Uplink

It is well known that the capacity for two users with powers p_1 and p_2 and gains g_1 and g_2 connecting simultaneously and continuously to a common receiver is [16]

$$C = W \log\left(\frac{p_1 g_1 + p_2 g_2}{W N_0} + 1\right) \quad (3)$$

It is also well known that if the temporal continuity constraint is relaxed, orthogonal signaling (such as time-division or frequency division) can also be used (theoretically) to achieve this bound [16]. In what follows we restrict ourselves to a single channel (no orthogonal signaling) and show that time-varying gains naturally imply a time-division one-at-a-time signaling structure for capacity maximization.

So, let $g_i(t)$ be the link gain between the infostation and user i at time t and define the instantaneous power transmitted by user i as $p_i(t)$. For given power profiles, the capacity is

$$C = \lim_{T \to \infty} \frac{W}{T} \int_{-T/2}^{T/2} L(t)\, dt \quad (4)$$

where

$$L(t) = \log\left(\frac{p_1(t) g_1(\mathbf{x}(t)) + p_2(t) g_2(\mathbf{y}(t))}{W N_0} + 1\right) \quad (5)$$

We now assume that the gain is a function of user position, $\mathbf{x}_i(t)$, and that the vector $\mathbf{x}_i(t)$ follows some ergodic independent stochastic process for each user. In that case C of equation (4) becomes

$$C = W \int_{\mathcal{A}} \int_{\mathcal{A}} \Pi_1(\mathbf{x}) \Pi_2(\mathbf{y}) \mathcal{L}(\mathbf{x}, \mathbf{y})\, d\mathbf{x}\, d\mathbf{y} \quad (6)$$

where

$$\mathcal{L}(\mathbf{x}, \mathbf{y}) = \log\left(\frac{p_1(\mathbf{x}, \mathbf{y}) g(\mathbf{x}) + p_2(\mathbf{x}, \mathbf{y}) g(\mathbf{y})}{W N_0} + 1\right) \quad (7)$$

$\mathcal{A}$ is the user position domain, and $\Pi_i()$ is the location probability density for an ergodic mobility process. We seek to maximize capacity by choosing optimal power profiles subject to some constraints on average power

$$\begin{aligned} P_i &= \lim_{T \to \infty} \tfrac{1}{T} \int_{-T/2}^{T/2} p_i(t)\, dt \\ &= \int_{\mathcal{A}} \int_{\mathcal{A}} \Pi_1(\mathbf{x}) \Pi_2(\mathbf{y}) p_i(\mathbf{x}, \mathbf{y})\, d\mathbf{x}\, d\mathbf{y} \end{aligned} \quad (8)$$

Applying the usual variational calculus [17] techniques results in an auxilliary function $F[p_1(), p_2()]$ as

$$F = \Pi_1(\mathbf{x}) \Pi_2(\mathbf{y}) \left[\begin{array}{c} \log\left(\frac{p_1(\mathbf{x},\mathbf{y}) g(\mathbf{x}) + p_2(\mathbf{x},\mathbf{y}) g(\mathbf{y})}{W N_0} + 1\right) \\ -\lambda_1 (p_1(\mathbf{x}, \mathbf{y}) - P_1) \\ -\lambda_2 (p_2(\mathbf{x}, \mathbf{y}) - P_2) \end{array} \right] \quad (9)$$

where λ_1 and λ_2 are non-zero Lagrange constraint constants. We then use Euler's equation, $\frac{\partial F}{\partial p_i} = 0$, to obtain

$$\Pi_1(\mathbf{x}) \Pi_2(\mathbf{y}) \left[\frac{g(\mathbf{x})}{p_1(\mathbf{x},\mathbf{y}) g(\mathbf{x}) + p_2(\mathbf{x},\mathbf{y}) g(\mathbf{y}) + W N_0} - \lambda_1 \right] = 0 \quad (10)$$

for the differential equation in $p_1()$ and

$$\Pi_1(\mathbf{x}) \Pi_2(\mathbf{y}) \left[\frac{g(\mathbf{y})}{p_1(\mathbf{x},\mathbf{y}) g(\mathbf{x}) + p_2(\mathbf{x},\mathbf{y}) g(\mathbf{y}) + W N_0} - \lambda_2 \right] = 0 \quad (11)$$

for the differential equation in $p_2()$. For all $\{(\mathbf{x}, \mathbf{y})\}$ where $\Pi_1(\mathbf{x}) \Pi_2(\mathbf{y}) \neq 0$ we have

$$p_1(\mathbf{x}, \mathbf{y}) = \frac{1}{\lambda_1} - \frac{p_2(\mathbf{x}, \mathbf{y}) g(\mathbf{y}) + W N_0}{g(\mathbf{x})} \quad (12)$$

and

$$p_2(\mathbf{x}, \mathbf{y}) = \frac{1}{\lambda_2} - \frac{p_1(\mathbf{x}, \mathbf{y}) g(\mathbf{x}) + W N_0}{g(\mathbf{y})} \quad (13)$$

which reduces to

$$p_1(\mathbf{x}, \mathbf{y}) g(x) + p_2(\mathbf{x}, \mathbf{y}) g(y) = \tfrac{g(x)}{\lambda_1} - W N_0 \quad (14)$$

in the solution for $p_1(\mathbf{x}, \mathbf{y})$ and

$$p_1(\mathbf{x}, \mathbf{y}) g(x) + p_2(\mathbf{x}, \mathbf{y}) g(y) = \tfrac{g(y)}{\lambda_2} - W N_0 \quad (15)$$

in the solution for $p_2(\mathbf{x}, \mathbf{y})$. Clearly unless both $g(\mathbf{x})$ and $g(\mathbf{y})$ are fixed constants over all $\{\mathbf{x}, \mathbf{y}\}$ such that $\Pi_1(\mathbf{x}) \Pi_2(\mathbf{y}) \neq 0$, these seemingly contradictory statements are resolved only if for $p_1(\mathbf{x}, \mathbf{y}) \neq 0$ we have $p_2(\mathbf{x}, \mathbf{y}) = 0$ and *vice versa* for all $\{\mathbf{x}, \mathbf{y}\}$. This observation, along with the positivity constraint on the $p_i()$ leads to

$$p_1(\mathbf{x}, \mathbf{y}) = \begin{cases} \left[\frac{1}{\lambda_1} - \frac{W N_0}{g(\mathbf{x})}\right]^+ & \text{when } p_2(\mathbf{x}, \mathbf{y}) = 0 \\ 0 & \text{otherwise} \end{cases} \quad (16)$$

in the solution for $p_1(\mathbf{x}, \mathbf{y})$ and

$$p_2(\mathbf{x}, \mathbf{y}) = \begin{cases} \left[\frac{1}{\lambda_2} - \frac{W N_0}{g(\mathbf{y})}\right]^+ & \text{when } p_1(\mathbf{x}, \mathbf{y}) = 0 \\ 0 & \text{otherwise} \end{cases} \quad (17)$$

Thus, users should never overlap their transmissions in time and there is also a set of positions outside which a user should never transmit, analogous to the single user results in [3–5].[1]

Of course, there are exceptions to the no-sharing rule. The first has already been considered: cases where $g(\mathbf{x})$ and $g(\mathbf{y})$ are fixed constants over some space of possible (non-zero probabiliy) mobile locations. Another arises when there are multiple channels available, as might be used in an Orthogonal Frequency Division Multiplexing (OFDM) signaling approach [18–21] or with multiple antennas [22]. Though sole use still applies on any one orthogonal channel, different users on different orthogonal channels are not constrained in regard to their temporal transmission schedules. However, we may conceptually (if somewhat awkwardly) sidestep this issue by defining the "fundamental infostation" as a single channel infostation. The result is that though the reception apparatus of many infostations may be co-located, each orthogonal channel corresponds to a single infostation and the sole use results still hold.

Finally, it should be noted that although the formulation was explicitly for two users, it can be easily extended to any number of independent users serviced by a single infostation.

III. Multiple Infostations, Multiple Users

Suppose users visit several infostations during a single connection. For example, a user might roam over a shopping mall with stores offering local infostation services and would not stay connected to a single infostation while shopping. Likewise on a highway with infostations at regular intervals, users might traverse great distances (from the fixed network perspective) between infostation contacts.

Now consider that data communication, such as web browsing, is inherently asymmetric with much greater volume occurring on the downlink from network to user. If the information is available at the infostation, then the main issue is to send it to the mobile as rapidly as possible. Since the data rate is high, as long as the user is in the coverage area, transfer may occur in a few seconds. However, if the information is *not* available at the infostation and has to be transfered from a server, then the information has to pass through the fixed network before reaching the mobile. Thus, in this "drive-through" scenario, since the coverage area is small, the time which the mobile spends in coverage at a given infostation may not be sufficient to transfer the information from the server to the infostation.

This is a situation peculiar to infostations where the radio rate is assumed to be much higher than the fixed network rate. Given an inexpensive high-speed radio, there are a number possible reasons for this inversion of the status quo. For economy, one could have a low cost relatively low rate connection (i.e. commodity telephone modems) to each infostation. Alternately, even if one connects the infostations with high speed links, some types of services (i.e. HTTP request) have typical transmission rates of the order of Kbits/second. The server transmission rate and network congestion play an important role in determining the speed of the connection. Another scenario would have fixed network links servicing some primary traffic with the infostation as an add-on service sharing these links. Finally, one might even have a relatively high rate fixed dedicated connection (DSL-like at upwards of 1 Mbps) but even there, completion of large transfers might not be possible if the user spends only a short time in coverage.

Thus, in all these cases, although the radio rate is high, the user would either have to restart a request or continue a request at the next infostation in the path. Either approach increases the delivery delay beyond the minimum possible [13].

The obvious solution to this radio/fixed-net mismatch is to cache information at the infostations. Storing pieces of information in convenient places became an attractive solution on the Internet [23,24]. A little bit different is the idea of *prefetching*. Web prefetching is based on the fact that, after retrieving a page from the remote server, a user usually spends some time viewing the page (so called think-time), when the network will be idle. During this time, files that are likely to be accessed in the near future can be fetched to the local disk, reducing the delay of loading the next page [25].

As an example, an intelligent prefetching algorithm which attempts to predict *what* the user will need was proposed as a solution to a location dependent application (map request) [11]. The algorithm uses location and speed information to select which of a set of maps should be prefetched. Based on location, time or user dependency, different types of applications would need different schemes for prefetching. However, suppose the information needed is *known* and can be of any sort such as a web page, a map, or personal e-mail. Then, the issue becomes how to partition the information, and then *when* and *where* to send the segments over the fixed network so that they arrive at the user with minimal overall delay. This is a *coordinated pre-delivery* process. In this paper the term prefetching is used to refer to the coordinated pre-delivery process, since the system is prefetching information to the mobile in several infostations.

Thus, consider a system where the infostations are connected as a *cluster* in a hierarchy where there is a higher level with a *cluster controller*, as shown in Figure 1. The cluster controller is the entity that has information on all requests that were made in that cluster and how many users are being served at every infostation in that cluster.

As the mobile user requests a file, the cluster controller can coordinate the delivery of some segments to the next infostation in the mobile's path, so that they are locally available at that infostation when the mobile user arrives in its coverage area. If the path is not known then the cluster controller can send the segments to infostations that are most likely to be in the mobile user's path. Therefore, during the time the user is going between two infostations, the system can download the

[1] Owing to space limitations, we omit explicit discussion of coverage region morphology for the multiple user case.

information to the next coverage area, reducing the delivery delay, as shown in Figure 1.

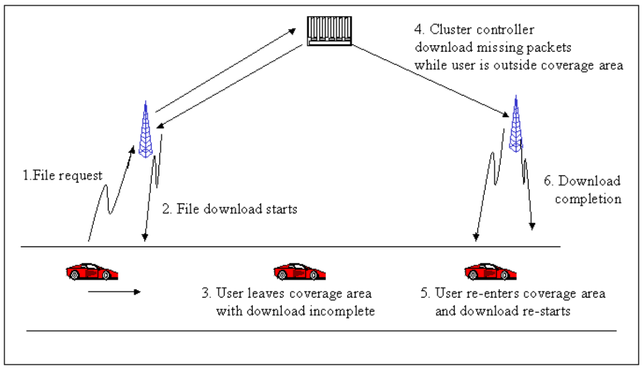

Figure 1: The problem approach

Previous work [1, 2, 13] considered a general infostations topology represented by an n-dimensional hypercube with a single mobile performing a random walk. Upper bounds on the average number of file segments picked after a given number of steps were derived. Heuristic algorithms that decide which segments to prefecth to the (single) user were studied. Given that the requested file can be divided in many different smaller segments, and each segment is labeled, the role of the algorithm is to decide, after every step, which segments should be sent to which infostations. The goal is to minimize the overall file transfer delay. Simulation results were presented showing that a near-optimal performance can be achieved using heuristics.

In this paper we will concentrate on the multiple user case. Our main goal is to understand which segments should be delivered to an infostation when several different users will pass through the infostation at different future times. We assume that the mobile users' paths are known, which is the best case scenario. We also assume that when a user is being served, an optimum algorithm will deliver the *right* segments to that user. It is important to note that the approach taken here is different than the one for the single user case, where we concentrate on *which segments* from a given user to transmit. The study of the multiple user case concentrates on *which user* to serve at any given time. If the user visits a large number of infostations before completion of file delivery, some approximations ease our analysis. We will show that, if the goal is to minimize the average delay, then resource sharing among users is suboptimal – a result consistent with the queuing literature for differing job sizes [26, 27].

A. Continuous Approximation

Suppose a given user arrives at infostation j. The user requests a file, but the time the user spends in the coverage area of infostation j is too small and only part of the file can be delivered. If the user is alone in the cluster (or if the system is lightly loaded), the file segments can be delivered to the next infostation in the user's path *while the user is in transit*. The question now arises as to how this fixed network bandwidth is to be allocated at each infostation. Specifically given an infostation which will be visited by multiple users during their sojourns in the system, whose file parts should be delivered when?

Let us first consider the simple problem in which there are two users, A and B, and let F_a and F_b be the size of the files requested by user A and B respectively. Assume that both users arrive at the system at the same time but at different positions, and have the same (constant) velocity. Assume for example that user A arrives at position 0 at time 0 and user B arrives at position 5 at time 0, as shown in Figure 2. We assume that one piece can be downloaded while the user drives between adjacent infostations and we represent a piece by a square in the figure. User A will request the file at infostation 0 and the prefetching process will start at infostation 1, with one piece, infostation 2 with two pieces, and so on, up to infostation 5. User B is at infostation 5. The prefetching process could start for user B: one piece at infostation 6, two pieces at infostation 7 and so on. Let us now assume that user A requested 30 segments. This means that some infostations where user B is will be needed to prefetch information for user A. Therefore there is an overlap of infostations where the system needs to decide which user to serve.

Clearly the first five infostations are dedicated to user A and at least five pieces are guaranteed to this same user at all infostations after infostation 5 (please see Figure 2. In a more general case, where user A is at position 0 at time 0 and user B is at position d at time 0, the first d infostations are dedicated to user A and at least d pieces are guaranteed to this same user at all infostations after infostation d.

The total number of segments that can be downloaded is given by the area under the curve. In this analysis we will approximate $\sum_{i=1}^{N} i = N(N+1)/2 = N^2/2$ and we will work with right isosceles triangles, as shown in Figure 2. This approach is valid when the number of infostations, N, is very large (or users request large files). This is what we call a *continuous approximation*.

Assume now that there are U users in the system and these users overlap and create common areas. A common area is the area where the system is not sure which user to serve. Again each user's prefetched segments can be represented by a triangle with possible holes. Inside each triangle we will find the common areas for that user. The same user can have different common areas, as shown in Figure 3, where users A and B have two different common areas. Obviously the common area that two or more users share is the same size for all those users. Although the common area is the same size, because the file sizes may be different, the size of the triangles formed by the prefetching information may be different for every user. Regardless, each triangle will have a part that represents the

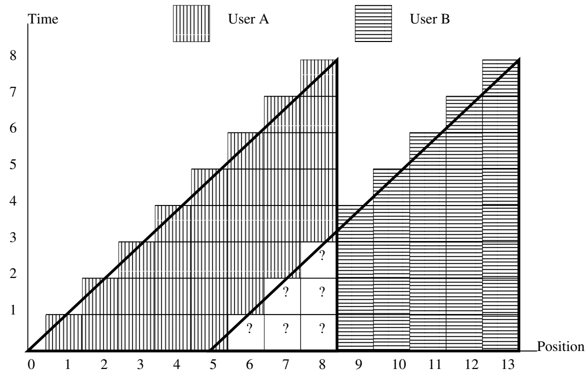

Figure 2: Two users: highway model with continuous approximation

user's segments and another part representing the shared area, as shown in Figure 4.

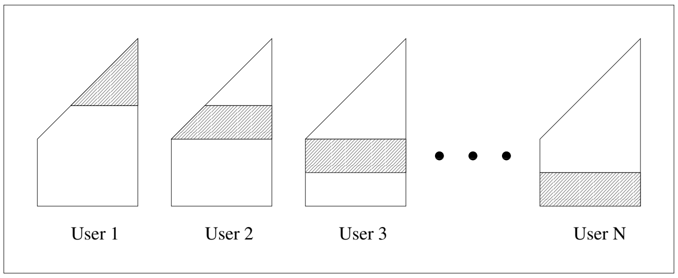

Figure 3: Example of common areas

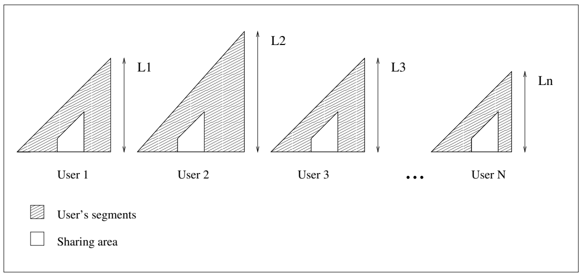

Figure 4: Prefetching segments represented by triangles

We say the system is *sharing* when it is serving more than one user in the common area and more than one of them do not receive their final pieces or if, at any time, more than one user is being served (in the common area) or if a user that receives all its pieces is served after one that does not. In other words, the system does not share when it gives priorities to users. We now prove, by contradiction, that the sharing approach does not minimize delay.

B. Do Not Share

Let us assume that there is an optimal solution where one of the common areas is shared among users (two or more users). Let D_S be the average delay given by this solution. Select now two of these users, j and k. Let L_j and L_k be the height of the triangle for user j and k, respectively, as shown in Figure 4. This is also the number of infostations which the users have to visit before completion of file delivery.

Assume that $L_j > L_k$. Then if one moves the segments that are in the common area and belong to user j to the end of user j's path, then one can move some of the segments of user k inside the common area. Let this be a solution S'. The delay of user j will increase to L'_j and the delay of user k will decrease to L'_k as shown in Figure 5. Therefore the average delay is now given by

$$D_{S'} = D_S + (L'_j - L_j) - (L_k - L'_k) \tag{18}$$

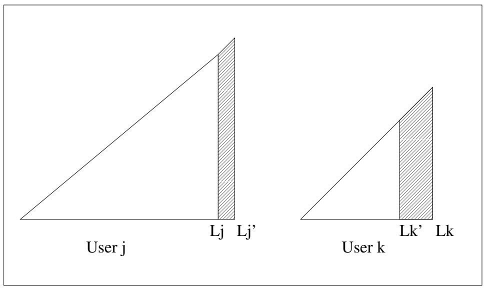

Figure 5: New delays: $L_j \to L'_j, L_k \to L'_k$

Since the areas of the trapezoids with heights $(L'_j - L_j)$ and $(L_k - L'_k)$ must be the same, and $L_j > L_k$ (which implies that $Lj' > L_k$), then

$$L'_j - L_j < L_k - L'_k \tag{19}$$

and therefore $D_{S'} < D_S$ and solution S was not optimum. This concludes our proof.

Therefore we conclude that, as in conventional processing systems [26], if the goal is to minimize delay, resource sharing is not a good approach.

IV. Conclusions

In this paper we presented a brief description of the infostation network and then considered the multiple access issues. We first studied the case of a single infostation and showed that in order to maximize capacity, the infostation radio should (almost) never be shared among users simultaneously. Note that we have assumed that the users are mobile. In the case of stationary users, one can imagine an infostation with a randomly swept beam to artificially generate an ergodic channel gain process – though not necessarily identical for each user. However, the problem formulation could be adapted to include non-identical ergodic channel gain processes.

We also considered fixed network coordination of file delivery for multiple users and multiple infostations. It was shown that the "sole use" paradigm evident over the radio channel is echoed when considering the backbone: In order to minimize average delay for large file sizes, the fixed link to any given infostation should serve users sequentially, as opposed to in a shared manner. This sole use attribute of infostations might greatly simplify control and coordination algorithms at both the radio level and the network level.

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