Towards an Asymmetric Air Interface Protocol for Wireless Internet Access

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Abstract. An asymmetric air interface protocol is one which allocates more capacity for one direction of data transfer (in our case, the downlink) than the other. In this paper we report ongoing work on the need and initial design calculations for an asymmetric indoor air interface protocol which is suitable for integrated voice and data applications, and specifically for wireless Internet access. As an example we consider PACS-UB, a symmetric protocol for voice communication in the isochronous unlicensed PCS band (1920-1930 MHz), and present a mechanism for making it statically asymmetric, as well as dynamically asymmetric in response to traffic demands. We also present a simplified worst-case two-dimensional model of co-channel interference when the air interface protocol is dynamically asymmetric. The quantitative results of the model indicate that an asymmetric protocol can result in significant gains in spectral efficiency. In the worst case downlink co-channel interference can be significant, and we discuss possible mitigating techniques that could be used.

1 Introduction

Wireless Internet access has been receiving increasing interest over the past year. While there exist wireless access technologies for Internet access, such as circuit-switched cellular, CDPD, RAM, and GSM, they have certain limitations. In particular, circuit-switched solutions are undesirable not only from the point of inefficient use of the wireless spectrum (since data traffic is bursty) but because of the congestion they create at the wired central office switches. Public packet radio data networks such as RAM and ARDIS, as well as the CDPD overlay network, suffer from low throughput (19.2 kbps or less). High-tier packet services, such as GSM's called GPRS [8], offer higher throughputs but may not be able to support many subscribers per cell. We are therefore examining the potential of packet-oriented low-tier PCS technologies for providing wireless Internet access.

One of the distinguishing features of the most common Internet applications (e-mail, ftp, gopher, WWW) is that they tend to be asymmetric in their bandwidth requirements, with the link to the user (the downlink) being far more heavily loaded than the link from the user (the uplink). It is therefore useful to consider an air interface protocol that allows asymmetric bandwidth allocation between the uplink and the downlink.

There are many different types of air interface protocols and Media Access Control (MAC) layer protocols being developed, with some of them targeting or mentioning Internet access as a motivating application. These include variations of PRMA [10, 15] or PRMA++ [2, 5, 6], and GSM [8, 7]. However, to our knowledge, none of them provide a mechanism to allocate the channel bandwidth asymmetrically for the uplink and the downlink. Wireless LANs do inherently provide a mechanism for asymmetric allocation of uplink and downlink bandwidths, since they typically use a mechanism similar to Ethernet's CSMA/CD protocol for access [12]. However, the asynchronous, unslotted nature of their air interface protocols is not efficient in terms of bandwidth usage, particularly when loads are high.

To consider the need for asymmetric air interface protocols, we use *spectral efficiency*, η, as the figure of merit, which is the number of simultaneous users per cell that can be supported by the system [11]. Consider the effect of asymmetric traffic in a symmetric system, i.e., a system where the bandwidth is divided symmetrically. We define the *traffic asymmetry factor,* A, as the ratio of traffic demand on the downlink to that on the uplink. Thus if the downlink is fully utilized, only $1/A$ of the uplink is utilized. Then the *usage factor*, i.e., the fraction of the combined bandwidth which is utilized, is given by

$$U = \frac{A+1}{2A} \tag{1}$$

Let η_s denote the spectral efficiency of a symmetric system with symmetric traffic; with asymmetric traffic, its spectral efficiency reduces to $\eta_s U$. The usage factor approaches 0.5 as A becomes large. For currently popular Internet applications, we postulate that the traffic asymmetry factor is likely to be large ($A > 10$). We consider conservatively low traffic asymmetry factors of $A = 2 - 4$ in this paper.

It is possible to design an air interface protocol which is statically asymmetric. In the case of a Frequency Division Duplex (FDD) system, a larger channel bandwidth is statically allocated to the downlink than the uplink, while in a Time Division Duplex (TDD) system, more time slots are allocated to the downlink than the uplink; similar arrangements can be made for CDMA systems. As an example, the PACS-UB protocol [13, 3], which was designed for voice communication in the isochronous unlicensed PCS band

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(1920-1930 MHz), and which uses TDD, can be modified to make it statically asymmetric. In sec. 2 we will discuss this possibility further.

It is desirable to have an air interface protocol where the degree of asymmetry is modified dynamically in response to traffic demands. In sec. 2 we will also discuss briefly, as an example, how the PACS-UB protocol may be made dynamically asymmetric, by utilizing some (nominally) uplink time slots for downlink transmission.

We recognize that there are several issues which need to be addressed further to determine the feasibility of dynamically asymmetric air interface protocols. One such issue is that of base station synchronization (we have considered methods for performing this, but omit further discussion for brevity.) Another critical issue is that of co-channel interference, since, unlike a symmetric or a statically asymmetric protocol, it is possible that users in co-channel cells might use the same time slot for the uplink and downlink simultaneously. In sec. 3 we present a simplified static worst-case analytical model for the quantifying this issue. In sec. 4 we discuss the results of the model and directions for further work.

2 Asymmetric PACS-UB

In this section we consider using a variation of the PACS-UB protocol as an example of an asymmetric air interface protocol for packet-oriented, integrated wireless voice and data communication; we also consider how it could be made dynamically asymmetric. The PACS-UB protocol [13, 3] was originally designed for voice communication in the isochronous unlicensed PCS band (1920-1930 MHz). We choose to consider the isochronous unlicensed PCS band for developing an asymmetric air interface protocol (as opposed to, say, the licensed PCS bands, the asynchronous unlicensed PCS band in the 1910-1920 MHz range or the NII band at 5 GHz) in general, and the PACS-UB protocol in particular, because:

1. We desire a protocol which can be used for both voice and data transfer over wireless.
2. The licensed PCS bands are allocated in inherently symmetrical pairs. An asymmetric FDD protocol, with some of the (nominally) uplink band being allocated for downlink transfers, would make terminal and base station hardware complicated and expensive.
3. The isochronous, slotted nature of the PACS-UB protocol is likely to have better bandwidth efficiency than asynchronous protocols, particularly at higher loads.
4. The etiquette for the 1920-1930 MHz band is already known and understood, and PACS-UB is designed to obey the etiquette.
5. There are no licensing fees for this portion of the spectrum.

The basic frame structure of PACS-UB is shown in Fig. 1. Each 312.5 μs burst contains a 10-bit Slow Channel (SC) and an 80-bit Fast Channel (FC) similar to PACS [9], providing a user bit rate of 32 kbps. The bursts are paired to form symmetric duplex channels as follows: (0, 2), (1, 3), (4, 6) and (7, 8); in Fig. 1 the uplink slots are shaded and labeled U0, U1, etc. Slot 7 also contains a System Broadcast Channel (SBC) which is used for sending control and signaling information from the base station to the mobile stations. In uplink slots U0 and U1 the mobile station (called the subscriber unit, SU, in PACS-UB terminology) can transmit data and tunes its synthesizer, respectively. In downlink slots D0 and D1 the SU can receive information and tunes its synthesizer, respectively. Uplink slots U2 and U3 are unused by this SU. In downlink slot D2 the SU makes measurements to decide whether an Automatic Link Transfer (ALT), i.e., a handoff, should be performed, and in D3 the SU tunes its synthesizer.

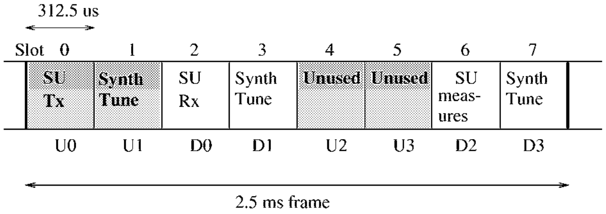

Figure 1: TDM/TDMA frame structure for PACS-UB

In addition to this frame structure PACS-UB maintains a 1-second superframe (i.e., consisting of 400 frames) in which the SBC information sent on the downlink on slot 7 is used to alert portables of incoming calls, broadcast system information, allow ports to obtain channel assignments, and allow portables to measure the channel for the appropriate port. Further superimposed on this 1-second superframe is a 30-second hyperframe used by the protocol to enforce the etiquette's 30-second Listen Before Talk (LBT) rule. We omit further details of PACS-UB; please see [13, 3].

We will consider a modification of PACS-UB to allow asymmetric bandwidth allocation. The basic idea is that the two uplink slots which are unused by the SU in the current frame structure (U2 and U3) are allocated to become downlink slots. For a static asymmetric protocol, this change suffices. For dynamic asymmetry, in addition:

1. During the 1-second superframe portables will inform the base station of their uplink and downlink bandwidth requirements. The base station will collect the requests from the portables into a batch, up to a short interval (e.g. 40 frames, or 100 ms) before the end of the superframe.
2. The base station will calculate a schedule for the frames of the following super-frame, i.e., will determine which of the frames of the following superframe will have U2 and U3 slots as uplink slots, and which will have them as downlink slots.
3. The base station will broadcast the schedule for the next superframe in the SBC during the last few frames of the current superframe.

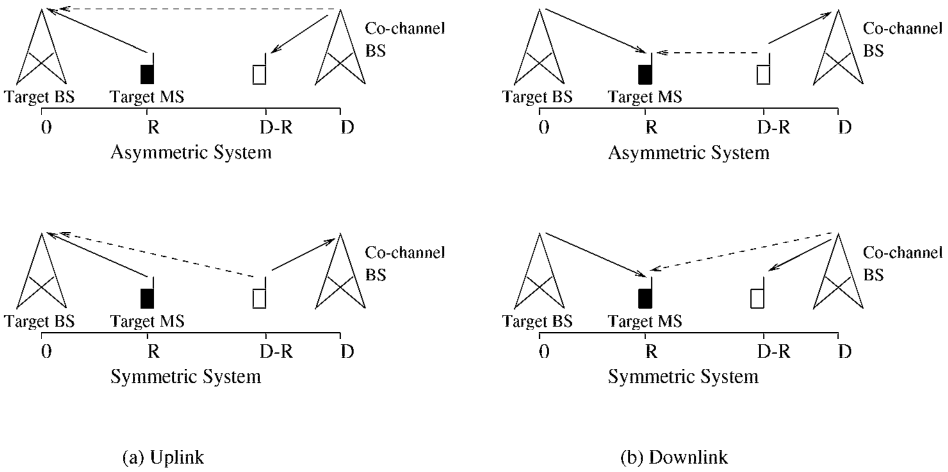

Figure 2: Worst-case scenarios for spectral efficiency comparison of asymmetric and symmetric systems. (Only one dimension is shown for simplicity.) Solid line: desired signal; dashed line: interference signal.

3 Co-channel Interference

We develop a simplified two-dimensional model for estimating the effect of co-channel interference for a dynamic asymmetric protocol in terms of spectral efficiency. The model assumes that received power decreases with distance following an inverse-power law, and for this "first-cut" analysis we ignore shadow, Rayleigh and multipath fading. While we have assumed the modified PACS-UB protocol as a motivation, the model developed in this section is more generally applicable.

If the total bandwidth allocation is W, the reuse factor, i.e., number of cells (or cell subsets) the total bandwidth is divided into, is K, and the bandwidth allocation per user is B, then the *spectral efficiency* [11] is

$$\eta = \frac{W}{BK} \tag{2}$$

We now assume worst-case scenarios for co-channel interference (see Fig. 2.) Let cells have radius R, assume transmission power decreases with distance following an inverse-power law with an exponent α, and the distance between co-channel cell centers is D.

Consider first an asymmetric system as shown in Fig. 2(a). In the worst case, when the target Mobile Station (MS) is using the uplink, its co-channel base stations (BS) e using the downlink simultaneously, causing interference at the target base station, i.e., the BS which the MS is transmitting to. Let the ratio of the transmission power of a BS to that of an MS be P. We consider the interference from the first ring of interfering transmissions only. If there are k interfering base stations ($0 < k < K$), the carrier-to-interference ratio at the target BS is

$$\gamma = \frac{R^{-\alpha}}{kPD^{-\alpha}} \tag{3}$$

Assuming hexagonal cells it is well-known [11] that $D/R = \sqrt{(}3K)$ so using Eq. 2, the spectral efficiency of the asymmetric system is

$$\eta_a = \frac{3W}{B(kP\gamma)^{2/\alpha}} \tag{4}$$

On the other hand, in a symmetric system, when the MS is using the uplink all co-channels will also be using that channel for the uplink. In the worst case, there will be an MS using the channel located at the edge of the co-channel cell such that it is as close as possible to the target BS. Then

$$\gamma = \frac{R^{-\alpha}}{k(D-R)^{-\alpha}}$$

$$\eta_s = \frac{3W}{B(1+(k\gamma)^{1/\alpha})^2} \tag{5}$$

We define the *spectral efficiency gain* as the ratio of the effective spectral efficiency of an asymmetric system to a symmetric system when offered asymmetric traffic, $g = \eta_a/(\eta_s U)$. For the uplink, using Eq. 1, 4, 5,

$$g_u = \frac{2A}{A+1}\left(\frac{1+(k\gamma)^{1/\alpha}}{(kP\gamma)^{1/\alpha}}\right)^2 \tag{6}$$

We can use the same approach as above to derive the spectral efficiency gain for the downlink. We omit details for brevity. For simplicity we make the assumption that, in the worst case, the average distance between the target MS and the interfering base stations is D. Observe that *this is a conservative assumption*, especially at small values of k, i.e., the actual interference in the worst case for the symmetric system can be higher. With this assumption, it can be shown that the spectral efficiency gain for the downlink is

$$g_d = \frac{2A}{A+1}\left(\frac{(k\gamma)^{1/\alpha}}{2+(\frac{k\gamma}{P})^{1/\alpha}}\right)^2 \tag{7}$$

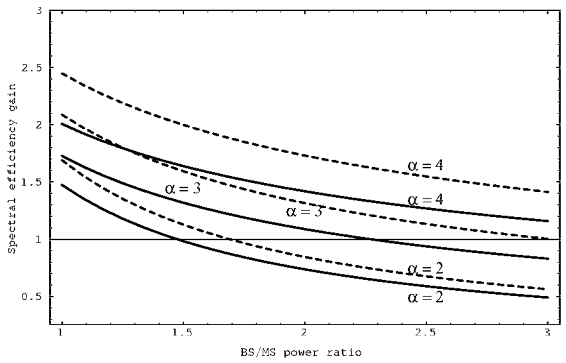

Figure 3: Uplink Spectral efficiency gain, g_u, vs. Ratio of Base station to Mobile station power, P. Traffic asymmetry $A = 2$. Dashed lines are for $k = 1$, solid lines are for $k = 6$.

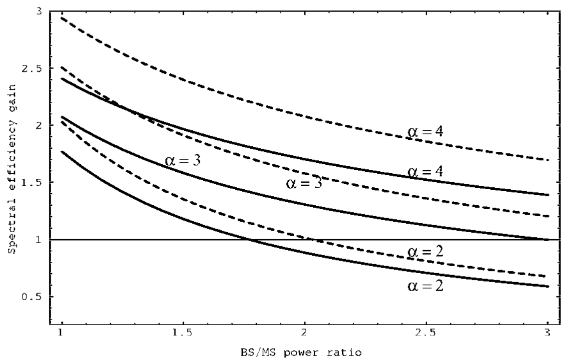

Figure 4: Uplink Spectral efficiency gain, g_u, vs. P, for $A = 4$.

3.1 Numerical results

We plot the spectral efficiency gain for the uplink and downlink as given by Eq. 6 and 7 for various parameter values in Figs. 3 - 6. For all plots we assume that the desired carrier-to-interference ratio, $\gamma = 18$ dB $= 63.1$. In all plots the dashed lines represent the case where there is one interfering (base or mobile) station, i.e., $k = 1$, and the solid lines represent $k = 6$. Observe that although the reuse factor K does not appear in Eq. 6 and 7, it is present implicitly since $0 < k < K$. For all the plots we assume that the reuse factor is $K = 7$. Each plot shows curves for $\alpha = 2$, 3, 4; this range of values covers most indoor propagation environments [4] [1].

We first consider the uplink. It can be seen from Figs. 3 - 4 that the asymmetric use of bandwidth can result in very significant gains in spectral efficiency on the uplink, even for relatively modest asymmetry in the traffic ($A = 2$), and this gain increases as the traffic asymmetry factor increases. It is interesting to see that the spectral efficiency gain can exceed $1/U = 2$. Thus the increase in spectral efficiency for the uplink is not due to the asymmetry of the traffic alone; from Fig. 2 we see that, for P close to 1 in our worst-case comparison scenarios, the asymmetric system also suffers from less uplink co-channel interference than the symmetric system.

Figs. 3 - 4 also show that the uplink spectral efficiency gain decreases as P, the transmission power ratio of BSs to MSs, increases. This is as expected since in the asymmetric system the interference is from BSs, while in the symmetric system it is from MSs; increasing the relative power of BSs favors the symmetric system.

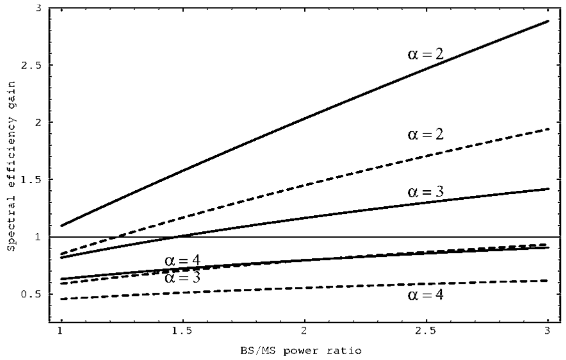

Figure 5: Downlink Spectral efficiency gain, g_d, vs. P, for $A = 2$.

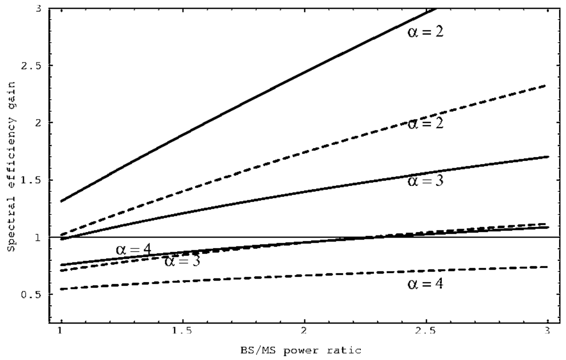

Figure 6: Downlink Spectral efficiency gain, g_d, vs. P, for $A = 4$.

We now consider the downlink. The results in Figs. 5 - 6 are unfortunately not as positive as for the uplink. Unless the transmission power ratio of BSs to MSs is increased to $P > 1.5$, i.e., about 2 dB, and there is a reasonable level of asymmetry in the traffic ($A > 2$), there can actually be a loss in spectral efficiency with the asymmetric system under the assumptions of our analysis. With $P = 2$ dB and $A = 3$, there can be a spectral efficiency loss of 40% if there are few interfering stations ($k = 1$) and propagation loss is high ($\alpha = 4$), or a net gain of up to 185% if there are many interfering stations ($k = 6$) and propagation loss is low ($\alpha = 2$). We omit further discussion of these results for brevity.

4 Discussion

Our simplified calculations indicate that the spectral efficiency gain of an asymmetric system on the uplink is somewhat offset on the downlink. Let the mean spectral efficiency gain (in the worst-case) be $g_m = (g_u + g_d)/2$. To maximize g_m, we set $g_u = g_d$; this amounts to finding the intersections of the curves in Figs. 3 - 4 with the corresponding curves in Figs. 5 - 6. We find that for $A > 2$ and $\alpha < 4$, there is still a (worst-case) mean spectral efficiency gain of about 20-50%, i.e., the number of users per cell which can be supported increases by about 20-50%. The mean spectral efficiency gain decreases as propagation loss (α) increases and the number of interfering stations (k) decreases.

The mean spectral efficiency gain relies upon being able to choose the BS/MS transmission power ratio, $P > 1$. For the parameter values considered, P needs to be at least 0.5 dB and values of 3 dB or more can be required. It remains open whether this is feasible in practice. The PACS-UB system design, for instance, assumes $P = 1$ [13, 3]. One possible option is to statically choose some fixed value $P > 1$ and maintain this power differential between base stations and mobiles at all times. Another possible option is to set $P > 1$ only for certain time slots, those where a downlink transmission may experience interference from simultaneous uplink transmissions. In the PACS-UB example discussed in sec. 2, this would mean setting $P = 1$ for all time slots except slots 4 and 5 (see Fig. 1). It is not clear whether modifying BS power on a time slot basis is desirable in practice. In either case, the impact of dynamic power control must be considered.

A possibility for avoiding the problem of downlink co-channel interference is to use a "guard band", such that in the first ring of interfering cells around the target cell, no simultaneous uplink transmissions are permitted. Such techniques are used in CDMA systems. Unlike the case of CDMA systems where the traffic is largely voice and hence symmetric, there is less likelihood of there being uplink traffic demand in the guard cells in our case. Another possibility is to use a dynamic channel interference measurement to prevent downlink co-channel interference. One such approach is to use an algorithm, such as the frequency segregation algorithm proposed in [14], which allows base stations to autonomously determine the appropriate channels for transmission.

Despite simplifications, the model indicates that significant gains (20 - 50%) in spectral efficiency can potentially occur with an asymmetric air interface protocol for wireless Internet access. We are thus currently studying some of the issues raised in this paper further. These issues include the impact of power control and traffic dynamics on the spectral efficiency of the asymmetric system under asymmetric traffic, as well as the potential use of dynamic power control, guard bands or dynamic interference measurement approaches to mitigate downlink interference.

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