DETERMINING BACKHAUL BANDWIDTH REQUIREMENTS FOR NETWORK MIMO

Howard Huang and Dragan Samardzija

Bell Labs, Alcatel-Lucent
791 Holmdel-Keyport Road, 07733, Holmdel, USA
email: hchuang, dragan@alcatel-lucent.com

ABSTRACT

In systems employing coordinated base station transmission and reception (also known as network MIMO), information needs to be shared among clusters of coordinated bases. This information includes coherent channel state information, user data, and baseband received signals. The cost of leasing and maintaining a reliable backhaul to share this information will be the dominant operational expense for cellular systems with network MIMO. In this paper we analyze the bandwidth requirements for sharing information among coordinated bases for network MIMO as a function of the coordination cluster size and channel characteristics. We find that for moderate Doppler speeds, the channel state information is a negligible fraction of the overall backhaul bandwidth. We also show that sending linearly quantized baseband signals over the backhaul achieves a significant fraction of ideal unquantized sum rate performance for uplink network MIMO based on zero-forcing.

1. INTRODUCTION

The throughput performance of cellular networks is fundamentally limited in conventional systems by the presence of co-channel interference from adjacent cells. *Network MIMO* is a class of transceiver techniques where the transmission and reception of signals among multiple spatially distributed base stations are coordinated so that interference is mitigated. Any network MIMO algorithm requires that information is shared among the coordinating bases. Specific network MIMO algorithms provide gains in throughput compared to conventional cellular networks for both downlink [1, 2] and uplink [3]. In general, the performance gains depend on both the transceiver algorithms and the size of the coordination clusters. The algorithms determine what types of information are shared among coordinating bases (for example, channel state information (CSI) and user data), and the cluster size determines the amount of information shared.

Information is shared by the bases on a wired or wireless backhaul connection, and the backhaul must be enhanced to support the higher bandwidth needs of network MIMO algorithms. Because the backhaul costs are a significant expense in cellular network operation, it is necessary to quantify the bandwidth requirements for various network MIMO system architectures.

Various system architectures are shown in Fig. 1. In a conventional cellular network, bases are connected over the backhaul to a radio network controller (RNC) which in turn is connected to the internet or phone network.

We classify network MIMO architectures and algorithms into one of two categories — either *full* or *limited* coordination — based on the information shared among the coordinating bases. Under full coordination, any necessary information is shared among the bases, including channel state information (CSI), user data, and side information required for signal processing. This architecture is functionally equivalent to having the base stations act as distributed antennas and having all baseband processing performed at a central controller (CC). On the downlink, implementation of multiuser MIMO algorithms such as zero-forcing beamforming across distributed antennas would fall into this category. On the uplink, MMSE or cancellation-based multiuser detection with multiple distributed receive antennas would also fall into this category.

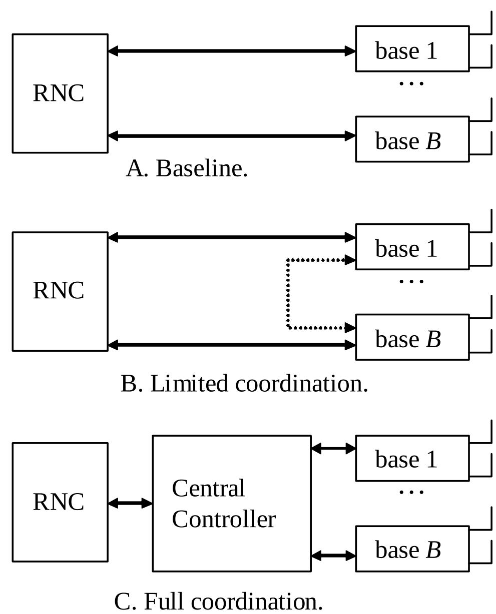

Figure 1: System architectures.

Under limited coordination, no user data is shared among the bases. CSI and other side information could be shared. If each base in a coordinated cluster has only a single antenna, intercell interference could be mitigated by coordinating the scheduling of transmissions across adjacent cells. For example, when a transmission occurs for a user at the cell edge, transmission from the adjacent cell is suspended. If each base has multiple antennas, then interference could be mitigated using spatial nulls steered in the direction of users in adjacent cells. More sophisticated interference alignment techniques [4] could also be used. Under limited coordination, information is shared among bases, but the baseband processing is performed locally at each base.

In this paper, we analyze the bandwidth requirements for sharing information among coordinated bases for these two categories of algorithms. In Section 2 we introduce the system model. In Section 3 we analyze the backhaul throughput requirements, while in Section 4 we focus on the baseband signal transport under full coordination. We conclude in Section 5.

2. SYSTEM MODELS

We consider a cellular network with B base stations serving a total of B users. For the conventional (baseline) and limited coordination cases, each user is associated with a serving base. For the fully coordinated case, all users are served simultaneously by all bases. We assume that each base station consists of M antennas and that each user (i.e., terminal) has a single antenna. We also assume a narrowband system with universal frequency reuse so that all transmissions occur on the same band. (The results can be generalized to account for multiple antennas and wideband OFDMA transmissions.)

For the downlink signal, we let x_k^{DL} denote the baseband data symbol for the kth user (k = 1, …, B). Under limited coordination where the ith base (i = 1, …, B) transmits to only its assigned user (which we assume has the same index as the base so that $k = i$), the transmitted signal at the ith base is

$$\mathbf{s}_i^{DL} = \mathbf{w}_i x_i^{DL} \ , \qquad (1)$$

where $\mathbf{w}_i$ is an M-dimensional precoding vector. For full coordination, we assume linear beamforming among multiple bases. We let $\mathbf{w}_{ik}$ be the M-dimensional precoding vector for the kth user's signal sent by the ith base (i = 1, …, B). The transmitted signal at the ith base is the sum of weighted user signals

$$\mathbf{s}_i^{DL} = \sum_{k=1}^{B} \mathbf{w}_{ik} x_k^{DL} \, . \qquad (2)$$

Let x_k^{UL} denote the scalar uplink baseband data symbol transmitted from the kth user (k = 1, …, B). We let $\mathbf{h}_{jk}$ be the M-dimensional complex amplitude vector between the kth user and the jth base (j = 1, …, B). The M-dimensional received signal vector at the jth base is the sum of signals from the users plus additive Gaussian noise

$$\mathbf{s}_j^{UL} = \sum_{k=1}^{B} \mathbf{h}_{jk} x_k^{UL} + \mathbf{n}_j \ , \qquad (3)$$

where $\mathbf{n}_j$ is the complex additive Gaussian noise received at the jth base. The expression in (3) is valid for both the limited and full coordination cases.

	Downlink		Uplink	
Baseline	From RNC	x_b^{DL}	to RNC	$\hat{x}_b^{UL}$
Limited coordination	from RNC	x_b^{DL}	to RNC	$\hat{x}_b^{UL}$
	from other bases	$\mathbf{H}_j$, $j \neq b$ or scheduling	from other bases	scheduling
	to other bases	$\mathbf{H}_b$ or scheduling	to other bases	scheduling
Full coordination	from CC	$\mathbf{s}_b^{DL}$ or ($\mathbf{W}_b$ and $\mathbf{x}^{UL}$)	to CC	$\mathbf{s}_b^{UL}$
	to CC	$\mathbf{H}_b$	to CC	$\mathbf{H}_b$

Table 1: Overview of required backhaul information, for b = 1, …, B.

3. ANALYSIS OF BACKHAUL REQUIREMENTS

In this section we determine the required backhaul data rates for network MIMO with limited and full coordination.

3.1 Baseline system

In a conventional system, all baseband processing is done locally at the base, and each base is assumed to serve a single user. For the downlink, the information bits corresponding to data symbol x_i^{DL} is sent over the backhaul from the radio network controller (RNC) to the base. Assuming an achievable spectral efficiency of C bps/Hz for each user and a channel bandwidth W Hz, the data rate from the RNC per base is

$$R_{base} = CW \text{ bps} \, . \qquad (1)$$

Likewise on the uplink, estimates of the information bits for the detected user are sent to the RNC. Assuming the same spectral efficiency, the data rate to the RNC is CW bps per base.

3.2 Limited coordination

Under limited network MIMO coordination on the downlink, the ith base transmits data for only its assigned user; however unlike the baseline case, the precoding vector $\mathbf{w}_i$ is designed to reduce interference for users in adjacent cells. Therefore base i needs to know the channel state information (CSI) between it and each of the users it intends to mitigate the interference towards. Most generally, if base i

serves user i and intends to mitigate interference for all other users, the precoding vector $\mathbf{w}_i$ is a function of all channel vectors $\mathbf{h}_{i1}$, …, $\mathbf{h}_{iB}$. Due to the channel reciprocity of the TDD system, the desired CSI could be obtained via uplink estimation of the channel vectors. No sharing of CSI between bases would be required.

Using a more general transceiver technique such as interference alignment [4], the precoding vector $\mathbf{w}_i$ is most generally a function of all base-to-user channel vector pairs. Computation of $\mathbf{w}_i$ could be done by a central processor given the CSI vectors from all bases $\mathbf{h}_{i1}$, …, $\mathbf{h}_{iB}$ (i = 1,…, B). Alternatively, each base could perform the computation locally if it received the CSI matrices from all other bases. Therefore base i would send $\mathbf{h}_{i1}$,…,$\mathbf{h}_{iB}$ over the backhaul to the other bases, and it would receive $\mathbf{h}_{j1}$,…,$\mathbf{h}_{jB}$ (j = 1, …, B, $j \neq i$) from the other bases.

If the channel is time-varying and frequency-selective, estimates of the CSI need to be sent only when significant changes in either time or frequency occur. Suppose the channel has a coherence bandwidth of W_C Hz and a coherence time of T_C seconds. If we require a 16-bit sample per I and Q dimension and 10 samples for each coherence bandwidth and time interval, the total required data rate for sending the M-dimensional CSI vector $\mathbf{h}_{ib}$ is $32M \times 10(W/W_C) \times 10(1/T_C)$ bps. With B bases, the total backhaul bandwidth for CSI per base is

$$R_{lim} = CW + \frac{3200MBW}{T_C W_C}\text{bps}. \qquad (5)$$

The ratio of the data and CSI backhaul rates, from (4) and (5), is

$$\frac{R_{lim}}{R_{base}} = \frac{C + 3200MB/\left(T_C W_C\right)}{C}. \qquad (6)$$

If we assume a typical pedestrian outdoor channel with coherence bandwidth W_C = 1 MHz, coherence time of T_C = 1 second, and we assume a spectral efficiency of C = 2 bps/Hz with B = 10 bases each with M = 4 antennas, the ratio in (6) is 1.06. Therefore the additional backhaul rate due to the CSI exchange for limited coordination is about 6% of the total rate for the conventional case. As the mobile speed increases, the ratio decreases as the backhaul overhead becomes more significant.

On the uplink, intercell interference can be mitigated if a base can estimate the CSI of users assigned other bases. This CSI estimation would be done directly on the pilot signals sent from the users, and knowledge of the CSI between the interfering user and *its* assigned base would not be useful.

Instead of CSI, scheduling information could be shared among bases, for example, to reduce the probability of two adjacent bases from simultaneously transmitting to users at their respective cell edges on the downlink. On the uplink, a similar strategy could be used to prevent simultaneous transmission by cell edge users. In cellular applications, the transmission interval is on the order of one millisecond. Only a few bits per transmission interval are required to convey the scheduling information. Compared to the data signal where typically thousands of bits are sent per interval, the scheduling information is a negligible fraction. Therefore like the sharing of CSI, the sharing of scheduling information has little impact on the backhaul requirements.

3.3 Full coordination

Under full downlink network MIMO coordination, each base station transmits data to all users. There are two options for sending information on the backhaul. One option is for the central controller to compute the precoding matrix $\mathbf{w}_i$ for base i (i = 1, …, B). The precoding matrix and the data for all users are sent to each base. The base station generates the baseband signal $\mathbf{s}_i^{DL}$ from (2), upconverts the baseband signal to RF, and transmits it. The data and frequency with which to convey the precoding matrices are similar to the requirements for conveying CSI. Therefore the bandwidth for precoding matrices is negligible compared to the bandwidth for user data. In this case, since B bases are sent to each user, the overall bandwidth requirement is a factor B greater than the baseline requirement.

As a second option, if a distributed antenna architecture is used to implement network MIMO, the baseband signal $\mathbf{s}_i^{DL}$ in (2) is sent from a central controller to base i (i = 1, …, B). The base station upconverts the baseband signal and transmits it. Similarly, on the uplink, the received signal is digitized and the resulting baseband signal $\mathbf{s}_i^{UL}$ is sent from base i to the central controller. In the following section, we discuss the quantization of the baseband signals for the fully coordinated case.

4. QUANTIZATION OF BASEBAND SIGNALS UNDER FULL COORDINATION

In this section we consider the transport network architecture that is depicted in Fig. 2. It is a star-like architecture that connects base stations with the central network MIMO controller. It corresponds to the distributed antenna architecture depicted in Fig. 1 C. For the sake of simplicity, in this section we will consider a single-antenna base stations and user terminals.

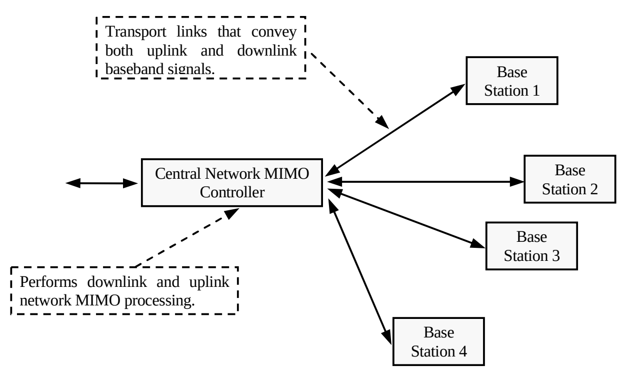

Figure 2: Transport network architecture.

From (2), the downlink signal that is sent by the central network MIMO controller to base station i is

$$s_i^{DL} = \sum_{k=1}^{B} w_{ik} x_k^{DL} \quad (7)$$

where w_{ik} is the downlink beamforming coefficient, and x_k^{DL} is the signal dedicated to single-antenna user terminal k. Similarly from (3), the uplink signal that is received by base station j and sent to the central controller is

$$s_j^{UL} = \sum_{k=1}^{B} h_{jk} x_k^{UL} + n_j \quad (8)$$

where h_{jk} is the uplink channel between base station j and terminal k, x_k^{UL} is the uplink signal transmitted by terminal k and n_j is the uplink AWGN. As a typical assumption, we will consider that the information-bearing signals x_k^{DL} and x_k^{UL}, for $k = 1,\ldots,B$, are distributed according to a circularly symmetric complex Gaussian distribution. Consequently, both the uplink and downlink signals, given in (7) and (8), are expected to have Gaussian distribution.

In order to transmit the signals over the transport links, the signals are quantized. Due to the quantization, a distortion is introduced. According to rate distortion theory, if on average R_T bits are used to quantize (i.e., source encode) the output of a unit-variance *iid* Gaussian source, the minimum mean square error D is

$$R_T = \log_2\left(1 + \frac{1-D}{D}\right) \Rightarrow D = 2^{-R_T}. \quad (9)$$

Note that the distortion D is achievable if the optimal quantizer, which incurs infinite delay, is applied [5].

If a transport link between the central controller and base station in Fig. 2 has the channel capacity C_T, optimal matching between the rate-R_T quantizer (i.e., the source encoder) and channel encoder results in the following relationship

$$R_T = C_T \Rightarrow D = 2^{-C_T} \quad (10)$$

The above relationship quantifies the minimum distortion D introduced due to the signal transmission over the transport link with the finite channel capacity C_T.

To quantify the effects of the finite transport channel capacity C_T, we consider the uplink network MIMO processing using the zero-forcing spatial filter. One-dimensional wrap-around topology is simulated (i.e., the base stations and terminals are on a circle), where the base stations are uniformly spaced. The terminals are randomly located. The path loss coefficient 3.5, independent shadowing with 8 dB standard deviation and independent Rayleigh fading is used to generate the channel coefficients h_{jk} between base station j ($j = 1, \ldots, B$) and terminal k ($k = 1, \ldots, B$).

In Fig. 3 the average user data rates, as a function of cell edge SNR are presented for a case of eight base stations and eight terminals (8x8), $B = 8$. Different transport link capacities are considered ($C_T \rightarrow inf$, $C_T = 8$, 12 and 16 bits/sym).

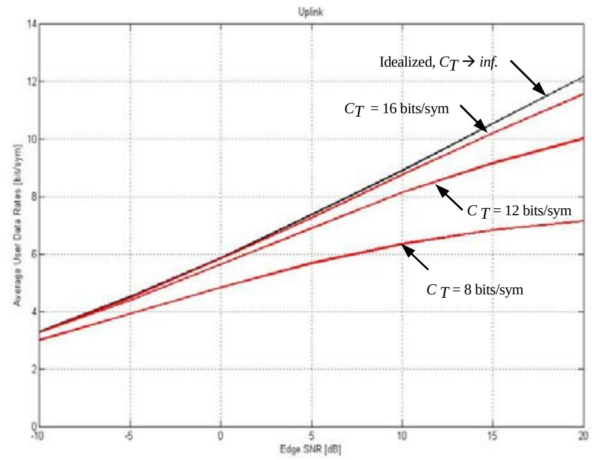

Figure 3: Uplink zero-forcing 8x8, optimal quantizer.

In Fig. 4 we present the ratio between average sum data rates for the transport system with $C_T = 16$ bits/sym versus the idealized one with $C_T \rightarrow inf$, given in percents. The results are presented for different number of base stations and terminals (i.e, coordination cluster size).

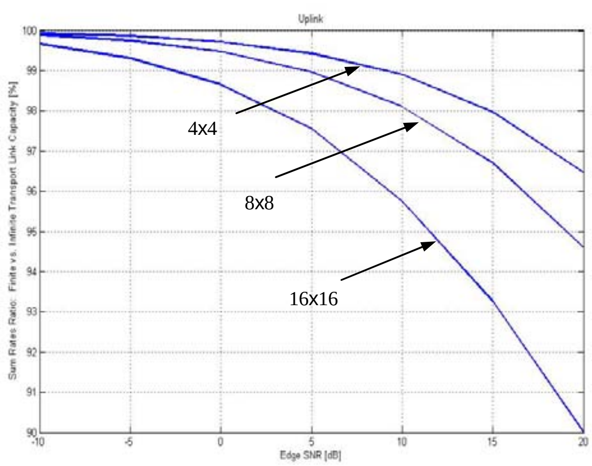

Figure 4: Uplink zero-forcing, 4x4, 8x8, and 16x16, and C_T = 16 bits/sym.

From the results presented in Fig 3 and 4 we note that the negative effects of the finite-capacity transport network are getting more pronounced for higher values of edge SNR and number of base stations and terminals (i.e., coordination cluster size). Accordingly, the transport network capacity should be dimensioned based on the expected channel conditions and the network MIMO coordination cluster size.

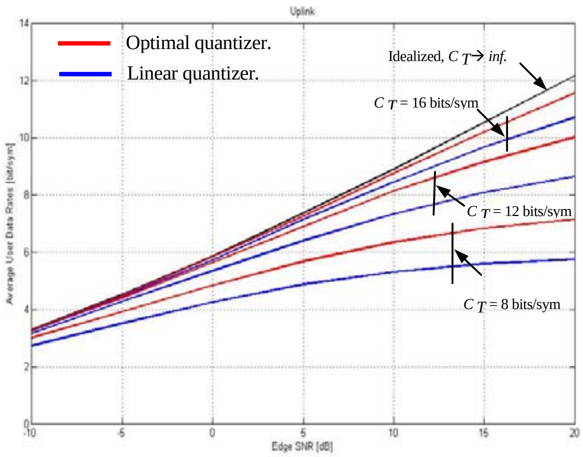

Figure 5: Uplink zero-forcing 8x8, optimal and linear quantizer.

The results presented in Fig. 3 and 4 should be viewed as upper bounds on performance since they relay on the optimal quantization, i.e., source encoding, which incurs infinite delay. Furthermore, to investigate more realistic scenarios we consider a linear zero-delay quantizer with a constant step size between the quantization levels. The step size is optimized for the given quantizer resolution R_T. Fig. 5 depicts the average user data rates corresponding to the scenario that was previously considered in Fig. 3. The performance of the linear quantizer is also depicted. It can be noted that the readily available linear quantizer underperforms the optimal one, but for moderate values of edge SNR, the 16-bit version is able to approach the optimal case (8 bits pre I and 8 bits per Q component). For higher values of edge SNR the performance between the two clearly diverges at the expense of the suboptimal linear quantizer.

5. CONCLUSIONS

We considered the backhaul bandwidth requirements for two classes of network MIMO architectures in comparison. Under a limited coordination architecture, bases share channel state information and/or scheduling information over the backhaul. Compared to a conventional cellular network where the user data is sent between the radio network controller and each base over the backhaul, limited coordination requires a negligible increase in backhaul bandwidth because the data rate of the channel and scheduling information is insignificant compared to the user data. Under a full coordination architecture, bases are connected to a central controller, and each base transmits data to all users served by a coordination cluster. Either the users' data streams are sent over the backhaul or a quantized baseband signal is sent. In the former case, the increased backhaul requirement is directly proportional to the number of bases in the coordination cluster. In the latter case, we showed that a simple linear quantizer with 16 bits per symbol is able to achieve a significant fraction of the ideal capacity for an uplink zero-forcing network MIMO algorithm.

REFERENCES

[1] M. K. Karakayali, G. J. Foschini, and R. A. Valenzuela, “Network coordination for spectrally efficient communications in cellular systems," *IEEE Wireless Commun*., vol. 13, no. 4, pp. 56-61, Aug. 2006.

[2] S. Jing, D. N. C. Tse, J. B. Soriaga, J. Hou, J. E. Smee, and R. Padovani, “Downlink macrodiversity in cellular networks," in *IEEE International Symp. Inform. Theory, ISIT 200*7, June 2007, pp. 1-5.

[3] S. Venkatesan, “Coordinating base stations for greater uplink spectral efficiency in a cellular network," in *Int. Symp. Personal, Indoor, Mobile Radio Commun. PIMR*C, Sept. 2007, pp. 1-5.

[4] V. R. Cadambe, S. A. Jafar, "Interference alignment and degrees of freedom on the *K*-user interference channel," *IEEE Trans. Inf. Theory*, vol. 54, no. 8, pp. 3425-3441.

[5] T. Berger, *Rate Distortion Theory: A Mathematical Basis for Data Compression*, Prentice-Hall, 1971.