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Spatially optimized wireless multicast networks with guaranteed bit-rate

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ABSTRACT

Multicasting is a mode of transmission in which the same information is relayed to a subset of users. Delivering the same information to multiple users of the subset via a series of one-to-one (unicast) transmissions quickly exhausts bandwidth. Delivering information in a series of one-to-all (broadcast) transmissions such that each subset receives its information in a round-robin manner causes latency, or equivalently, a reduction in bandwidth.

The techniques of this disclosure estimate the angular locations of each multicast subset using channel state information received across an antenna array. The locations are clustered using machine learning models. The available transmit power is allocated amongst clusters via spatially directed beams. The power allocation is designed to optimize the aggregate multicast bit rate while guaranteeing a minimum per-user bit-rate. Relevant information is beamed in a focused manner to each multicast subset, thus increasing the throughput to a subset while reducing interference to other subsets.

KEYWORDS

multicast network; beamforming; smart antenna; power allocation; water filling; bit allocation; space division multiple access; quality of service; QoS guarantee; channel capacity

BACKGROUND

Multicasting is a mode of group communications in which the same data is transmitted to multiple users that form a subset of all users. A special case of multicasting is broadcasting, wherein the same data is transmitted to all users. Another special case of multicasting is unicast, wherein each subset comprises just one user. An example of a multicasting is a video server sending out one TV channel to a specific set of users.

Delivery of high bit-rate data streams to users within a multicast subset via a series of unicast transmissions quickly exhausts the capability of even high bandwidth networks. This poses a scalability challenge for applications that require a minimum guarantee of quality of service.

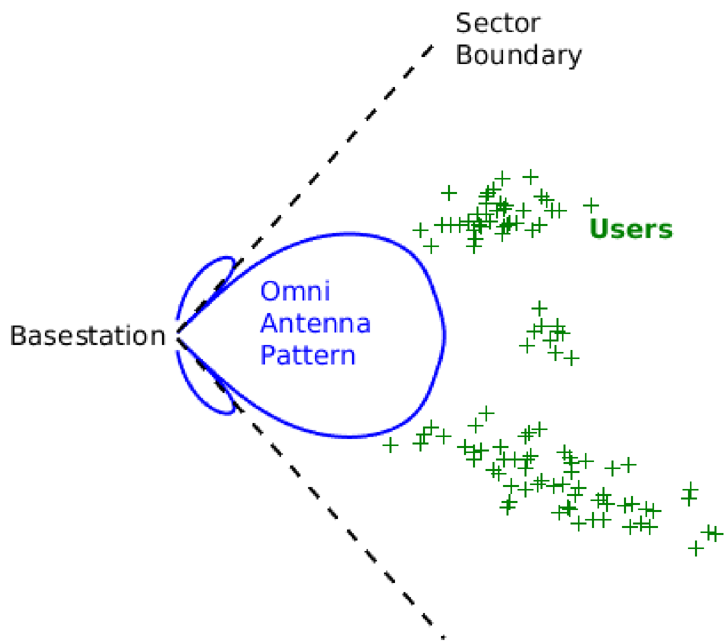

Fig. 1: Omni-directional radiation pattern for spatially separable users is sub-optimal

In the context of wireless multicast, current wireless technologies typically use an omni-directional radiation pattern, e.g., transmission has equal energy in all directions, even if the multicast subsets are spatially separable. This is illustrated in Fig. 1, where the antenna radiation pattern is almost uniform across its sector although the spatial distribution of users is concentrated at certain angles. In Fig. 1, there are regions without users towards which the base station nevertheless expends (and wastes) energy.

Phased arrays (also known as smart antennas or beamforming arrays) are a technique that can direct radio frequency (RF) energy to particular subsets of users. Phased arrays are a collection of antenna elements that act in consort to drive energy (beamform) towards an intended direction. The RF energy of a phased array is steered by changing the amplitude and phase of the signal on each antenna element, which in turn creates a constructive/destructive interference pattern at the wavefront. Constructive interference is designed to occur at the location of the intended receiver, thereby giving that receiver a directional gain, which translates to improved link capacity. The directionality of the emitted RF energy also reduces the interference perceived by other users.

DESCRIPTION

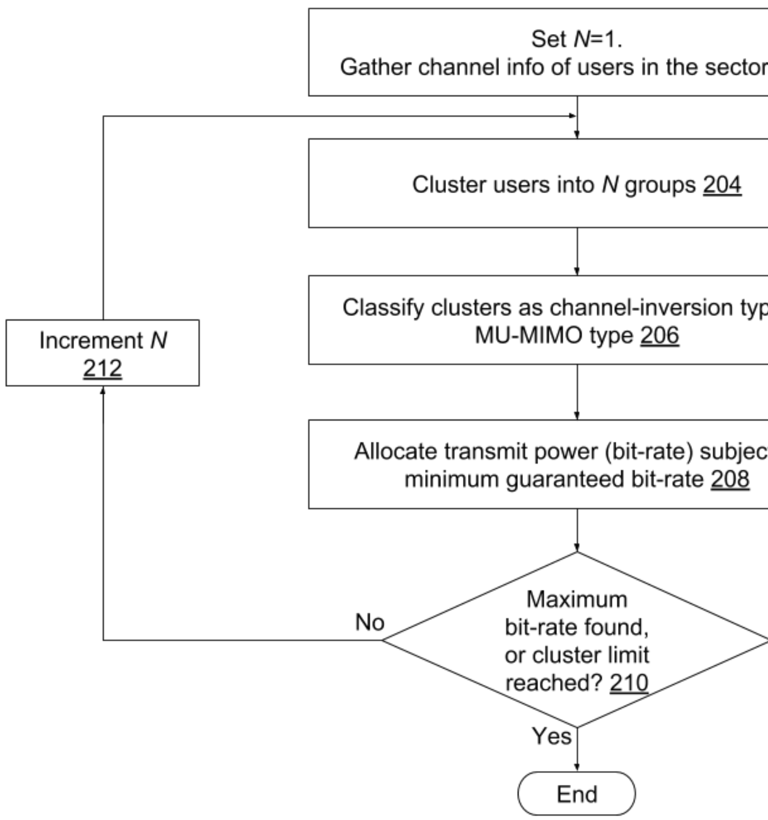

Fig. 2: Optimizing aggregate multicast bit-rate subject to a minimum guaranteed per-user bit-rate

Fig. 1 illustrates a flowchart of an example method to optimize aggregate multicast bit-rate subject to a minimum guaranteed per-user bit-rate, per techniques of this disclosure. At block 202, the number of clusters *N* is set to unity. The base station gathers the channel state information (CSI) and the signal to interference plus noise ratio (SINR) of each user. The base station computes the angle of arrival of each user (ϕ_i) from the CSI information.

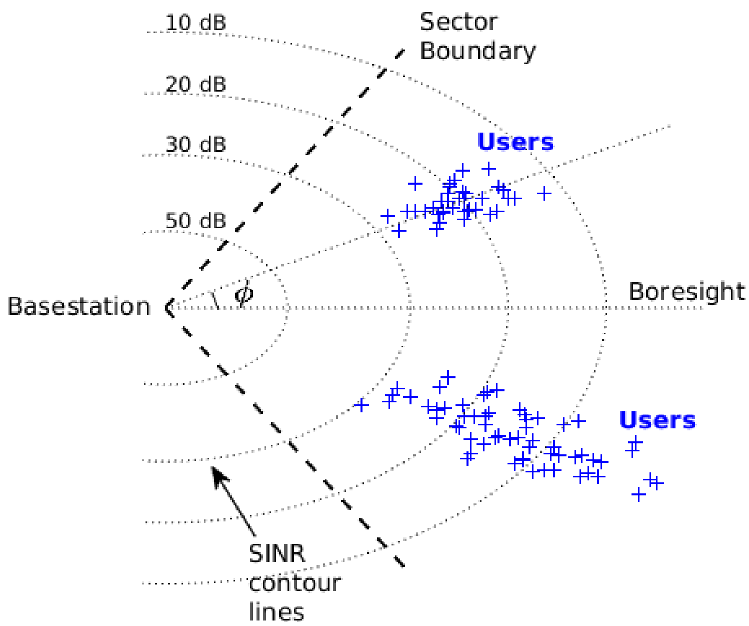

Fig. 3: Angular (ϕ) and SINR map for multicast users in a sector

The result of the angle-of-arrival computation is a spatial map of users against the angles of arrival, illustrated, for example, in Fig. 3.

At block 204, the users are grouped into clusters based on the angles of arrival. Example clustering techniques utilized for such grouping include k-means, k-means++, Gaussian mixture models, clustering by machine learning, etc.

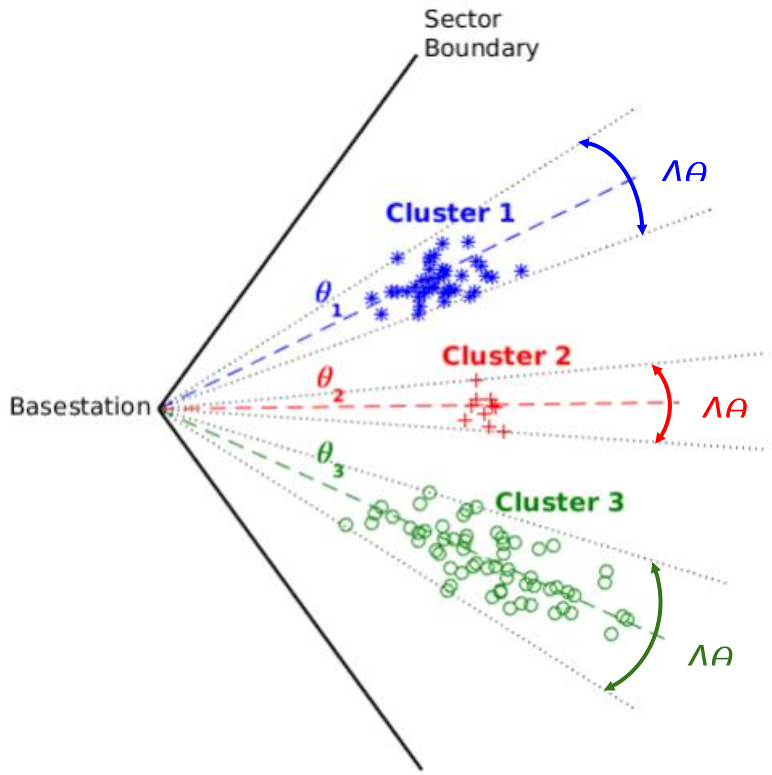

Fig. 4: Clustered user groups

As illustrated in Fig. 4, clustering results in the identification of the angular center (θ_i) and width or span ($\Delta\theta_i$) of each cluster. Clustering is performed such that the angular center of each cluster is separated at least by the beamwidth of the phased array of the base station. The value of the beamwidth is a design parameter, and depends, e.g., on base station hardware and target performance. Typically, beamwidth is taken as the angular width at which the directional gain falls by 3 dB with reference to peak directional gain. For example, an eight-element, planar phased array with half-wavelength element spacing has a 3 dB beamwidth of approximately 12.5 degrees. The base station can be configured with an arbitrary phased array geometry, element spacing, and number of radiating elements.

At block 206, the clusters are classified as being of type channel inversion or multi-user multi-input-multi-output (MU-MIMO), as follows. For cluster *i*,

- if the boundaries of the cluster are spaced from the boundaries of its neighbors (e.g., clusters *i-1* and *i+1*) by less than (or equal to) the null-bandwidth of the array, then the clusters *i-1*, *i*, and *i+1* become part of a *j*th channel inversion set; and
- if the boundaries of the cluster are spaced from the boundaries of its neighbors (e.g., clusters *i-1* and *i+1*) by more than the null-bandwidth of the array, then the *i*th cluster becomes part of the MU-MIMO set.

The rationale for assigning clusters to one of two types is that clusters that are too close (the channel inversion set) use the same modulation/packet format to avoid inter-cluster interference. On the other hand, clusters that are sufficiently spaced away from each other (the MU-MIMO set) can use a different modulation/packet format since beamforming by the base station minimizes inter-cluster interference.

At block 208, transmit power (e.g., bit-rate) is allocated to each cluster via beamforming by optimizing the following cost function.

$$\begin{aligned}
\max \quad & \sum_{i}^{\text{all clusters}} N(i) \cdot \min(\ \text{Capacity}\{\text{all users} \in i^{th}\, \text{cluster}\}\ ) \\
\text{s.t.} \quad & \text{Modulation}\{\text{all clusters} \in j^{th}\ \text{“}\textit{Inverse Channel Set}\text{”}\} = \textit{same} \\
& \min(\text{Capacity}\{\text{all users}\}) \geq \text{minimum desired rate} \\
& \sum_{i} P_i \leqslant P_t
\end{aligned}$$

where

$N(i)$ is the number of users in the *i*th cluster;

P_i is the power allocated to the *i*th cluster;

P_t is the total available power;

Capacity{user} is the supportable bit-rate for a user given the SINR of the user;

Modulation{cluster} is the modulation, e.g., QPSK, 16-QAM, etc., and error-correcting code applied to a cluster; and

minimum desired rate is the per-user guaranteed bit-rate.

The optimization is carried out using standard numerical techniques over P_i, the power allocated to the ith cluster, such that the sum of allocated powers is less than the total available power.

At block 210, the aggregate bit rate, e.g., over all users of all clusters, resulting from the optimization is found. If the aggregate bit rate is a maximum, or if the cluster limit is reached, then the optimization procedure terminates. If not, the number of clusters N is incremented (212), and another iteration is carried out to obtain a better aggregate bit rate.

The power or bit allocation procedure described above maximizes the weighted sum capacity of the lowest-SINR user of each cluster. The rationale for doing so is that in multicast, it is the lowest-SINR user that sets the modulation (e.g., bit-rate) for the entire group. The power or bit allocation procedure weighs the capacity of the lowest-SINR user of a cluster by the total number of users within that cluster, since clusters with more users are to have a higher cluster-wide bit-rate. If the clusters are too close (e.g., they belong to a channel inversion set), then they receive the same modulation/packet format in order to forestall inter-cluster interference.

To further clarify the techniques, two extreme cases are examined.

1. **All clusters are too close (e.g., all part of a channel inversion set):** In this case, the power or bit allocation procedure reduces to a max-min problem where it tries to maximize the throughput of the lowest-SINR user of all sectors, with all sectors using the same modulation. The power or bit allocation for each cluster is just enough for the lowest-SINR user to decode transmissions of the base station. If the lowest-SINR user for

each cluster is the same for all clusters, then the procedure converges to an omni-directional radiation pattern with equal power distribution over the entire sector, e.g., as illustrated in Fig. 1.

2. **All clusters are sufficiently apart (e.g., all part of the MU-MIMO set):** In this case, the power or bit allocation procedure is similar to water-filling in the spatial domain, where higher-capacity (higher-SINR) clusters receive better power allocations (and vice-versa), while the lowest-capacity cluster still receives a guaranteed minimum bit rate. In this context, the capacity of a cluster is measured as the capacity of the lowest-SINR user of the cluster multiplied by the number of users in the cluster.

Generally, the power or bit allocation procedure seeks a balance between the above two extremes, since, in practice, the base station is most likely find a mix of clusters that are too close and clusters that are sufficiently far apart.

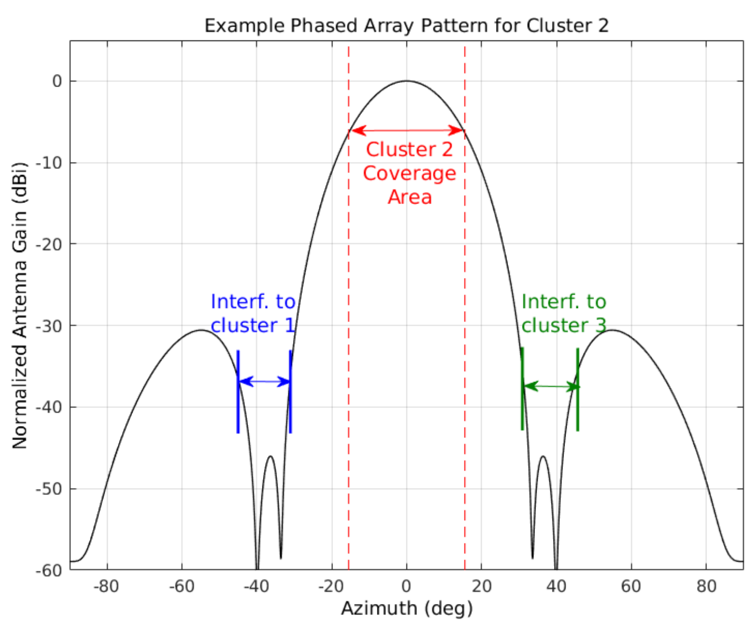

Fig. 5: Radiation pattern of a phased array that is targeting RF energy at cluster 2 (near zero degrees azimuth) while minimizing RF energy at clusters 1 and 3 (near ±40 degrees)

To maximize gain in the direction of a targeted cluster and minimize interference to other clusters, the base station applies tapering or steering weights to elements of its phased array. The result of applying steering weights is illustrated in Fig. 5, which shows substantial relative gain in the direction of a targeted cluster (cluster 2) and minimal gain in the directions of other clusters (clusters 1 and 3). Techniques to compute steering weights include Chebyshev, Taylor, convex optimization, etc. The steering weights used for Fig. 5 are computed by convex optimization.

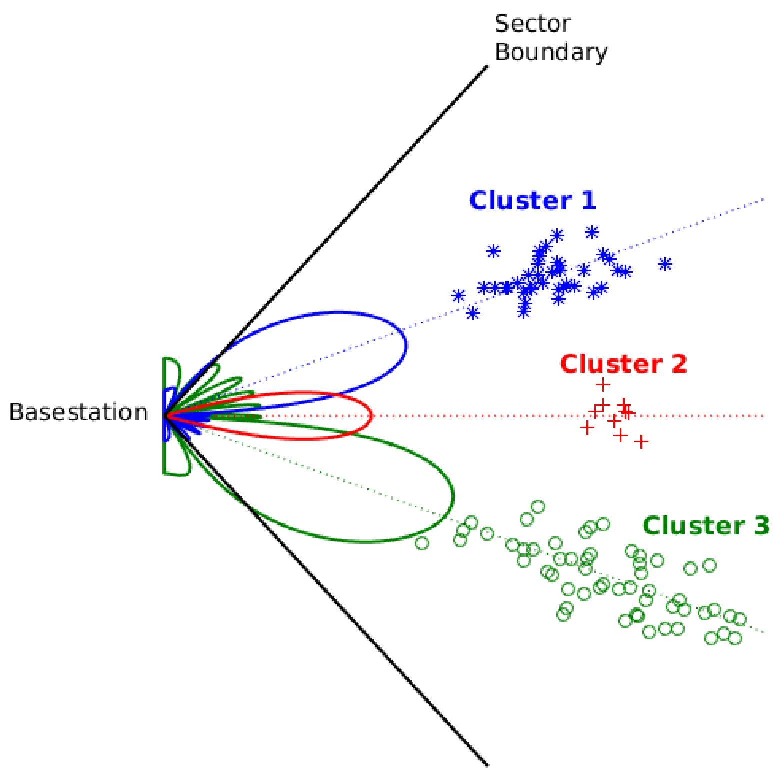

Fig. 6: Radiation patterns resulting from the power or bit allocation procedure of this disclosure

Fig. 6 illustrates radiation patterns resulting from the power or bit allocation procedure described above. It is worthwhile to compare Fig. 6 with the unoptimized (omni-directional) radiation pattern of Fig. 1. In Fig. 6, each cluster receives a radiation pattern that is directionally focused towards itself while minimizing interference to other clusters. The power allocated to each cluster, illustrated by the peak amplitude of its radiation pattern, is proportional to the capacity of each cluster. Thus, cluster 3 (green) receives a higher power allocation due to the greater number of users and greater capacity. The reverse applies to cluster 2 (red), although per the techniques herein, even the lowest-capacity cluster is guaranteed a certain minimum bit rate.

CONCLUSION

The techniques of this disclosure estimate the angular locations of each multicast subset using channel state information received across an antenna array. The locations are clustered using machine learning models. The available transmit power is allocated amongst clusters via spatially directed beams. The power allocation is designed to optimize the aggregate multicast bit rate while guaranteeing a minimum per-user bit-rate. Relevant information is beamed in a focused manner to each multicast subset, thus increasing the throughput to a subset while reducing interference to other subsets.

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