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# Cooperative Multicasting Based on Superposition and Layered Coding

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***Abstract*—Cooperative diversity plays an important role in achieving efficient multicast transmissions for wireless applications. In this paper, we propose a novel two-phase cooperative multicast scheme based on superposition coding. In the first phase, the Base Station (BS) broadcasts a composite message. Most of the subscribers in the multicast group will decode the base message and the subscribers who experience better channel conditions will decode the enhancement message (referred to as the first enhancement message) as well. In the second phase, a fraction of the subscribers who decoded the first enhancement message, cooperatively transmit the first enhancement message to the subscribers who failed to decode it. The remaining subscribers who successfully received the first enhancement message will not participate in the cooperative transmission and will receive a second enhancement message transmitted by the BS. The proposed scheme exploits spatial diversity gain across multiple subscribers to maintain higher average throughput for each subscriber in addition to enabling scalable delivery of multimedia data. Simulations show that, under the same total energy consumption, the proposed scheme outperforms the conservative scheme and schemes exploiting cooperative relaying or superposition solely.**

***Index Terms*—Wireless multicast, cooperative relaying, superposition coding, wireless multimedia.**

## I. Introduction

Multimedia broadcast and multicast have been attracting great attention in the last few years. Various multimedia services gained great popularity recently, such as Internet Protocol TV (IPTV) and mobile TV, increasing the importance of efficient transmission algorithms that utilize the system resources to serve the subscribers.

In multicast transmission, subscribers who demand the same service are grouped logically to form a multicast group. Data is transmitted simultaneously to all subscribers in the multicast group. The dynamically changing characteristics of the wireless channels along with the multipath fading and path loss make each groups' subscribers experience different channel conditions. The diverse channel conditions of multiple subscribers in the multicast group makes it a challenge to adapt the transmission rate to satisfy all group members and improve the total group throughput, simultaneously.

A simple multicast scheme has been developed for CDMA 2000 1xEV-DO networks by taking a default transmission rate ignoring the diverse channel conditions among different subscribers [1]. A general approach conservative multicast scheme uses the transmission rate accommodating the worst channel conditions in the group. Such scheme makes the multicast group throughput controlled by the worst channel conditions. As a result, all the subscribers in the multicast group get the service at the same, low quality, level.

Multicast systems are mainly used for video transmission. Many advanced scalable video codecs have been proposed to improve the scalability of video transmission. These codecs enable partial decoding, thus, the video quality increases with the number of quality layers that the receiver decodes correctly. In [2], the authors proposed two-level SuperPosition Coded Multicasting (SPCM) scheme for IPTV. A multicast signal is generated by superimposing the base quality layer bit stream, modulated with a low-order modulation scheme to the enhancement quality layer. The base layer contains essential information to decode the video stream while the enhancement layer contains information to enhance the quality of the video. Hence, subscribers with bad channel conditions can decode base layer only, while other subscribers decode both base and enhancement layers to get better video quality.

In addition to service scalability, delivering multimedia service to subscribers experiencing bad channel conditions is a great challenge in multicast transmission. Recently, Cooperative transmission has been a subject of great interest among the research community. It is considered as a desirable enhancement to future systems and is being evaluated for the 4G standards Long Term Evolution-Advanced (LTE-Advanced) [3], [4] and WiMAX [5]. Subscribers in a wireless network help each other by forwarding data, aiming at increasing each subscribers capacity and the aggregate multicast group capacity. Decode and Forward (DF) protocol is widely used in cooperative transmission [6]. Such a scheme divides the downlink time slot into two phases. In the first phase, the BS broadcasts a message to all subscribers in the multicast group. In the second phase, relays that correctly decoded the message forward it to the subscribers who failed to decode the message during the first phase. In [7], a fixed number of relays take turns to forward packets, and layered video coding is used to provide subscribers with different video quality. The authors in [8] proposed Cooperative Multicast Scheme (CSM) where all subscribers who correctly decode the message transmitted by

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the BS in the first phase, serve as relays and simultaneously forward the packets in second phase. The work in [9] used a maximal ratio combiner to enhance the received signal-to-noise ratio (SNR) in a distributed cooperative multicast scheme. Although several cooperative strategies have been proposed, there are pitfalls that need to be investigated. For example, subscribers with good channel conditions are deprived from achieving higher throughput due to their employment in cooperative relaying in the second phase and are not given the opportunity to increase their throughput.

In this paper, we propose a scheme that utilizes cooperative transmission with layered video coding and superposition to enable an efficient video multicast transmission. The scheme exploits the spatial diversity gain across multiple subscribers by using two-phase cooperative transmission with superposition coding. In the first phase, the BS broadcasts a composite message of a base and first enhancement layer. The base message will be decoded by most of the subscribers in the multicast group, while the first enhancement message will only be decoded by the subscribers who experience better channel conditions. In the second phase, based on the subscribers' SNR, a fraction of the subscribers cooperatively broadcast the first enhancement message. The remaining subscribers who successfully received the first enhancement message will not participate in the cooperative transmission and will receive a second enhancement message that is transmitted by the BS in the second phase. The scheme allows subscribers with the best channel conditions to get the multimedia service at the highest data rates and enhances the rate of subscribers who experience low SNR. Compared to CMS, SPCM and the conservative scheme, the proposed scheme is shown to achieve higher average multicast throughput under the same total energy consumption. The proposed scheme enhances scalable multimedia delivery by providing different rates in the same transmission slot.

The rest of the paper is organized as follows, Section II reviews the system model for multicasting environment. Section III introduces the proposed cooperative superposition relaying scheme. In Section IV the achievable rates of the proposed schemes are studied, while Section V presents the simulation results to demonstrate the effectiveness of the proposed scheme. Finally, Section VI concludes the paper.

## II. System Model

A wireless network with one cell of radius $R$ is considered. The BS is located in the center of the cell and $M$ subscribers are randomly distributed in the cell. Signals from the BS to the subscribers are subject to path loss and Rayleigh fading. The received signal is affected by Additive White Gaussian Noise (AWGN). The channels for different subscribers are assumed independent and identically distributed (i.i.d.). Perfect channel estimation is assumed at all receivers. All the transmitting nodes are perfectly synchronized and the delay spread of the channel is negligible, which is a valid assumption for narrow band wireless communications as stated in [10].

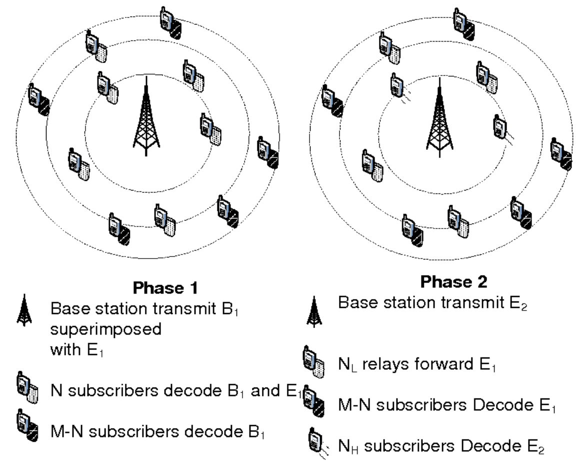


Fig. 1. The proposed Multicast Cooperative Scheme

The signal received by subscriber $i$, $y_i$ can be expressed as

$$y_i = h_i \sqrt{P_d d_i^{-n}} x + n_i \tag{1}$$

where $x$ is the signal transmitted by the BS, $h_i$ is the Rayleigh fading channel gain between the BS and subscriber $i$ modeled as a zero-mean circularly symmetric complex Gaussian random variable with unit variance, $h_i \sim CN(0, 1)$. $n_i$ is AWGN with variance $N_0$, $n_i \sim CN(0, N_0)$ and $P_d$ is the transmitting signal power. $d_i$ is the distance between the BS and subscriber $i$, $n$ is the path loss exponent used to relate the average received signal power with the transmitted signal power. The model used ensures that $P_R \propto \frac{P_T}{d_i^n}$, where $P_R$ and $P_T$ are the received and transmitted powers respectively.

Due to the dynamic nature of the wireless channels, the received SNR varies with time and subscriber location. If transmission rates are determined according to the subscribers who experience good channel conditions, subscribers with bad channel conditions will fail to decode data. On the other hand, if transmission rates are determined based on the worst channel condition, all the subscribers will get the service with a low rate, lower than what they can accommodate based on their channel conditions.

## III. The Proposed Scheme

The objectives of the proposed scheme are to increase the average multicast group throughput and deliver the service to subscribers experiencing bad channel conditions, while enabling scalable delivery of multimedia data. Figure 1 illustrates the principle of the proposed cooperative multicast scheme. In this scheme, the downlink frame $T$ is divided into two phases of durations $T_1$ and $T_2$. The multimedia transmission in the two phases is discussed as follows:

### A. First Phase

Using layered coding, the multimedia stream can be coded into multiple streams allowing partial decoding at the receiver at different layers. An example for superposition modulation

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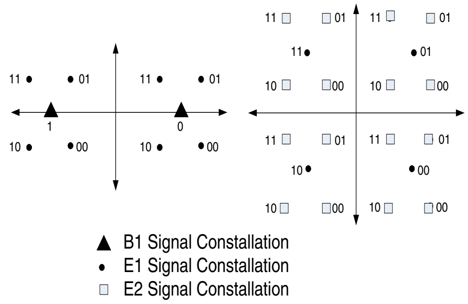


Fig. 2. Signal constellation for modulation used in cooperative scheme

is illustrated in figure 2. The BS broadcasts a signal which is a composite message of base layer $B_1$ and first enhancement layer $E_1$ with rates $R_{B1}$ and $R_{E1}$, respectively.

The base layer rate is low to enable most of the subscribers to get the service at a basic level. $N$ out of $M$ subscribers, with good channel condition, can decode both $B_1$ and $E_1$ with negligible probability of error. Let the set $S_N$ has the N subscribers who achieve the higher data rate, resulting in a better quality of the multimedia service.

### B. Second Phase

The subscribers in set $S_N$ are subdivided into two sets $S_{NH}$ and $S_{NL}$ depending on the received SNR in the first phase. The sets $S_{NH}$ and $S_{NL}$ have $N_H$ and $N_L$ subscribers respectively, where $N = N_H + N_L$ . Therefore, in the second phase subscribers are divided into three sets as follows:

1) $S_{NH}$ has the $N_H$ subscribers who successfully decoded $E_1$ in the first phase and their received SNR is higher than a certain threshold $\gamma = 2^{R_{E2}} - 1$, where $R_{E2}$ is the rate of the second enhancement layer $E_2$.
2) $S_{NL}$ has the $N_L$ subscribers who successfully decoded $E_1$ in the first phase and their received SNR is lower than $\gamma$.
3) $S_{M-N}$ has the $M-N$ subscribers who failed to decode $E_1$ in the first phase, but some of these subscribers decoded $B_1$ correctly.

In the second phase of the downlink, the procedure goes as follows:

- $N_L$ subscribers serve as relays and cooperatively transmit the message $E_1$ with rate $R_{E1}$.
- The BS broadcasts $E_2$ with rate $R_{E2}$.
- The $M - N$ subscribers decode the message $E_1$ that is transmitted by the $N_L$ relays. Only subscribers who managed to decode $B_1$ will benefit from successful reception of $E_1$ in the second phase.
- The $N_H$ subscribers decode the message $E_2$ after canceling the effect of the interference caused by the cooperative relays.

In the first phase, subscribers in the set $S_{M-N}$ fail to decode $E_1$ due to bad channel conditions with the BS. In the second phase, cooperative transmission enhances the rates of the set $S_{M-N}$. The enhancement is due to exploiting the spatial diversity provided by the relaying subscribers in the cell.

A key element in the proposed procedure that should be noted is that the interfering signal received power caused by the BS transmission of $E_2$ is low compared to $E_1$ received power. This is due to the already bad channel conditions on the direct link between the BS and the subscribers in the set $S_{M-N}$. This is evident since all the subscribers in the set $S_{M-N}$ failed to decode $E_1$ transmitted by the BS with the same power correctly in the first phase. Therefore, the signal power of $E_2$ should be limited and not to exceed the signal power of $E_1$ in the second phase.

Before the $N_H$ subscribers decode $E_2$, they eliminate the interference effect of the cooperative relays transmission using prior knowledge of the message $E_1$ and the channels gains to the other subscribers. This is a result of the fact that the received signal is the superposition of $E_1$ and $E_2$.

To decrease processing overhead on the BS, all rates will be determined based on long term channel conditions as in [8]. The scheme enables scalable multimedia delivery by providing three different rates for three sets of subscribers. The scheme exploits the capability of the subscribers experiencing good channel conditions to receive service at high rates and high quality of service.

Choosing the rates $R_{B1}$, $R_{E1}$ and $R_{E2}$ is critical for the system performance. These rates determines the number of subscribers in the three sets stated above. Accordingly, the system can be driven to enhance the throughput of the subscribers experiencing good channel conditions by increasing the number of subscribers in the set $S_{NH}$ or to enhance the throughput of subscribers experiencing bad channel conditions by increasing the number of cooperative relays in the set $S_{NL}$.

For controlling the system thresholds, used to determine $N_H$ and $N_L$, two new parameters are introduced: coverage ratio $C$ and cooperative ratio $\alpha$. The coverage ratio is the percentage of subscribers, on average, that can correctly receive the first enhancement layer rate $R_{E1}$ in the first phase and is given by $C = E(N)/M$. The cooperative ratio is the percentage of subscribers, on average, that work as relays in the second phase and is given by $\alpha = E(N_L)/M$.

$R_{E1}$ is determined based on the coverage ratio $C$ in the first phase. As $C$ increases, $R_{E1}$ decreases to enable more subscribers to receive $E_1$ in the first phase, i.e. $N$ increases. As $C$ decreases, $R_{E1}$ increases and a lower number of subscribers will be able to decode the enhancement layer correctly in the first phase.

$R_{E2}$ is determined based on $\alpha$ in the second phase. As $\alpha$ increases more subscribers cooperate in transmission in the second phase, i.e. $N_L$ increases. Increasing $N_L$ improves the probability that the subscribers in set $S_{M-N}$ decode $E_1$ correctly in the second phase. Since the set $S_{NH}$ has the subscribers with the highest SNR from the set $S_N$, increasing $\alpha$ decreases $N_H$ resulting in higher $R_{E2}$ and vice versa.

The parameter $\alpha$ controls the system by either favoring subscribers with high received SNR on the expense of subscribers with low SNR, or enhancing the system fairness by increasing the number of cooperative subscribers $N_L$ which leads to higher throughput for subscribers with low SNR.

## IV. ACHIEVABLE RATES

For the Rayleigh flat fading channel, given a received SNR, the maximum achievable data rate with a negligible error probability is $\log_2(1+SNR)$ for unit bandwidth [11].

### A. First Phase

According to the scheme described in Section III, in the first phase, the BS broadcasts a composite message to the $M$ subscribers. Each subscriber $i$, receives the signal

$$y_i = h_i\sqrt{d_i^{-n}P_d}S_1 + n_i \quad (2)$$

where $S_1$ is the signal transmitted by the BS generated by the superposition of $B_1$ and $E_1$. An example for the signal constellation that can be used in superposition is illustrated in Figure 2. According to [12], a subscriber can decode the base layer if

$$R_{B1} \leq \log_2\left(1+\frac{|h_i|^2\bar{a}d_i^{-n}P_d}{|h_i|^2 a d_i^{-n}P_d + N_0}\right) \quad (3)$$

where $a$ and $\bar{a}$ is the percentage of power used for enhancement and base layer transmission respectively, such that $a+\bar{a}=1$.

If a given subscriber managed to decode the message $B_1$ correctly and assuming perfect channel estimation, the receiver can subtract the base message from the received signal and can decode the enhancement message correctly if

$$R_{E1} \leq \log_2\left(1+\frac{|h_i|^2 a d_i^{-n}P_d}{N_0}\right) \quad (4)$$

### B. Second Phase

$N$ out of $M$ subscribers decode the enhancement message correctly in the first phase by satisfying the condition in equation (4). $N_L$ out of these $N$ subscribers serve as relays in the second phase and cooperate to simultaneously forward the message to the $M-N$ subscribers with equal power $P_{dr}$. In the same phase, the BS broadcasts a message $E_2$. The received signal for a given subscriber $i$ is given by

$$y_i = \sum_{j=1}^{N_L} h_{i,j}\sqrt{d_{i,j}^{-n}P_{dr}}S_2 + h_i\sqrt{d_i^{-n}aP_d}S_3 + n_i \quad (5)$$

where $S_2$ is the message transmitted by the cooperative relays, which is the encoded version of $E_1$, and $S_3$ is the second enhancement layer message $E_2$ transmitted by the BS. For system power constrain, it is assumed that $N_L P_{dr} = (1-a)P_d$ so that total power consumed in the second phase is equal to $P_d$.

A given subscriber $i \in S_{M-N}$ can correctly decode the cooperative message in the second phase, transmitted with rate $R_{E1}$ according to the following condition,

$$R_{E1} \leq \log_2\left(1+\frac{\left|\sum_{j=1}^{N_L} h_{i,j}\sqrt{d_{i,j}^{-n}P_{dr}}\right|^2}{|h_i|^2 d_i^{-n} a P_d + N_0}\right) \quad (6)$$

For a subscriber $k \in S_{NH}$, and due to the knowledge of the message $E_1$ and the channel knowledge, the message $E_1$ can be subtracted from the received signal and the subscriber can decode the second enhancement layer if

$$R_{E2} \leq \log_2\left(1+\frac{|h_k|^2 a d_k^{-n}P_d}{N_0}\right) \quad (7)$$

## V. SIMULATION RESULTS

In this section, simulations are conducted to demonstrate the performance of the proposed scheme. We consider a circular cell of radius $R = 100$ with the BS located in the center of the cell, $n = 4$ and $a = 0.3$. The multicast group members are 30 subscribers randomly distributed in the cell according to the uniform probability density function of $d$ and $\theta$. For a given subscriber, the joint probability density function of the distance between the subscriber and the BS $d$ and the angle $\theta$ is given by $f(d,\theta) = d^2/\pi R^2$ with $0 \leq d \leq R$ and $0 \leq \theta \leq 2\pi$. The marginal distribution of $d$ is given by $f(d) = 2d/R^2$ and $\theta$ is uniformly distributed over the range $[0, 2\pi]$ [10].

For fair comparison, the total energy consumption over the transmission period is equal for all schemes employed in the simulation. The transmitted power in the first and second phases are equal (Pd = 85dB) for both CMS and the proposed scheme.

Figure 3 demonstrates the effects of $\alpha$ on every subscriber throughput for a fixed $C$. Subscribers are sorted in a descending order according to their received SNR. For a fixed coverage ratio $C = 50\%$, when $\alpha$ increases, subscribers with low received SNR achieved higher throughput. This is because the number of subscribers that cooperate in transmission in the second phase increases. When $\alpha$ decreases, throughput of subscribers with low SNR is affected but more subscribers are able to achieve higher throughput due to receiving data in the second phase.

Figure 4 compares the average throughput of the proposed scheme with the conservative scheme, CMS proposed in [8] and SPCM proposed in [2]. $C$ is defined for CMS as the percentage of subscribers who decodes correctly in the first phase. SPCM utilizes superposition where a multicast signal is generated by superimposing the base quality layer bit stream, modulated with a low-order modulation scheme to the enhancement quality layer [2]. For SPCM, $C$ express the percentage of subscribers who decode both the base and enhancement layers correctly. The conservative scheme gives the lowest average throughput. The proposed scheme gives a better performance than conservative, CMS and SPCM for $C = 50\%$. In addition, the proposed scheme has more flexibility in controlling the performance of the subscribers with high SNR or the subscribers with low SNR and enhances the ability of scalable multimedia service delivery.

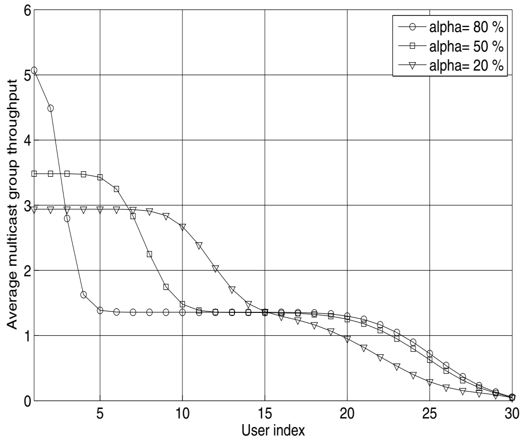


Fig. 3. Average subscriber throughput for different values of alpha and C=50%

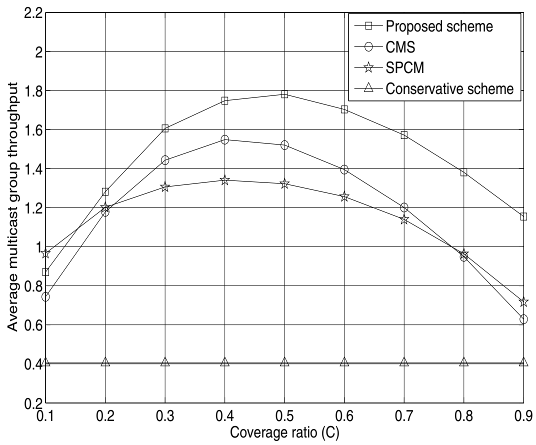


Fig. 4. Average multicast group throughput for different values of C

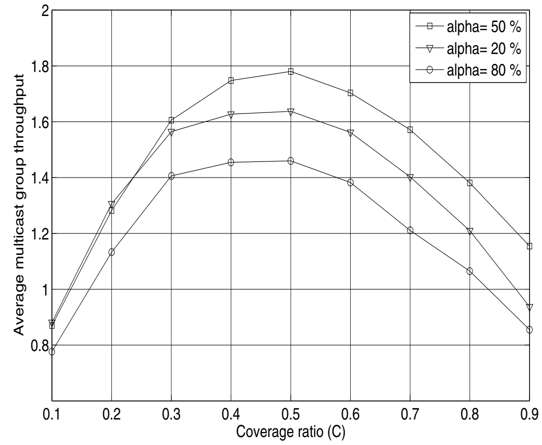


Fig. 5. Average multicast group throughput for different values of $\alpha$

Figure 5, demonstrates the effect of $\alpha$ on the average group throughput for different values of $C$. For high values of $\alpha$, the average throughput is lower because most of the subscribers cooperate in transmission and do not receive new data in the second phase. As $\alpha$ decreases, the average throughput increases until most of the subscribers who decode correctly in the first phase, receive data in second phase. In other words, a small number of subscribers cooperate to transmit, which affects the throughput of the rest of the subscribers in the cell, resulting in decreasing the average throughput of the multicast group. As shown in the Figure, $\alpha = 0.5$ is almost always better than $\alpha = 0.2$ or $0.8$.

## VI. CONCLUSION

In this paper, a high-throughput cooperative multicast scheme based on superposition coding is proposed. Such a scheme gives more degrees of freedom to drive the system either to higher data rates for subscribers with good channel conditions or to enhance the rate of subscribers with bad channel conditions. The scheme enhances the ability of scalable delivery of multimedia data by providing different rates for different subscribers resulting in different quality of service achieved among subscribers. Simulations show that, under the same total energy consumption, the proposed scheme gives higher average throughput for the multicast group than conservative scheme and schemes exploiting cooperative relaying or superposition solely.

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