Collaborative Signal Multiple Access: A Robust Alternative to NOMA Using SIC

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Abstract—We propose a novel non-orthogonal multiple access scheme referred to as collaborative signal multiple access (CSMA) to address key challenges of non-orthogonal multiple access (NOMA) enabling its use for future 5G/6G mobile systems. It provides higher capacity and robust operation in diverse wireless systems. A base-station groups small number of users to transmit their data simultaneously using power and signal space domains. A receiver performs collaborative joint detection of all users' data using minimum Euclidean distance criterion to extract only the desired user's data with minimal loss of signal energy. This approach is able to tolerate much wider power differences to operate in extreme co-channel interference scenarios where NOMA using successive interference cancellation (SIC) fails even under infinite signal-to-noise ratio (SNR). We provide extensive analyses and simulations supported by upper bounds on symbol error rates (SER) for different power allocation and M-QAM constellations. Numerical results confirm superiority of the proposed scheme in error performance and resulting capacity compared to NOMA, making it a very robust and practical alternative.

Index Terms—NOMA, high capacity, successive interference cancellation, M-QAM, joint detection

I. INTRODUCTION

NOMA has received widespread attention as being a promising approach to increase the sum rates of wireless access [1]–[7]. Interests on practical implementation of NOMA are also growing as evidenced by its inclusion as a study-item in 3GPP [2], [3]. It relies on the SIC method to cancel inter-user interference and is known to outperform orthogonal multiple access schemes in terms of sum rates when channel gain disparity between users are high [1]. However for the SIC method to work reliably it needs to meet very stringent conditions of power distribution among users, or else, it fails to decode its own user data due to high interference [5], not to mention the fact that grouping of users becomes very challenging [7], [10]. Furthermore, near equal power allocation and non-degraded broadcast channel condition represent other acute problems for NOMA SIC receivers as they are unable to decode the interference and hence ends up with error floor [6]. These issues are only exacerbated as the number of users

grow. Therefore NOMA is still not included as work-item in the 3GPP and left possible inclusion in beyond 5G [4].

We address some of these critical issues of NOMA with a new collaborative approach called CSMA—where users' signals are not treated as interference or noise—and detail its system design. This is inspired by the authors' early work on CDMA multi-user detection problem [9]. The CSMA approach makes use of the knowledge of all users' transmitted modulation symbol alphabets and power information to jointly detect and estimate all users' data by exploiting the fact that any of the possible location of a composite received signal is uniquely identifiable on the complex plane. A distinct difference between CSMA and NOMA SIC is, the latter requires received constellation points between each nearest neighbours to be within fixed partitions to decode user data and regenerate interference. However with CSMA, any of the constellation points can be unevenly spaced to support much wider range of power allocated to users at the transmitter. Unlike most of work on the NOMA literature e.g. [1], [5], [6] which require strict user power control to ensure SIC method works satisfactorily, we show here that CSMA can operate well even under the equal power for users and maintain decent SER. We provide theoretical analysis of SER of CSMA using minimum distance method to derive SER upper bounds and validate them with numerical simulations. Furthermore, we provide extensive comparative studies to confirm its superiority against NOMA in large majority of practical cases.

II. SIGNAL AND SYSTEM MODEL

We consider a downlink system with K users being served by a single base-station (BS). The composite constellation of K users s , transmitted from the BS as shown in Figure 1, can be written as:

$$s = \sum_{k=1}^K \sqrt{\alpha_k P_t} x_k, \quad (1)$$

where α_k is a power allocation coefficient consisting of a fraction of the total power P_t such that $\sum_{k=1}^K \alpha_k = 1$. The constituent modulated symbol of each user x_k is taken from a square M-QAM constellation with symmetric in-phase i_k and quadrature q_k components as follows:

$$x_k = i_k + \sqrt{-1}q_k. \quad (2)$$

Each user's symbols have alphabet of size M_k i.e. $x_k \in \mathbb{X}_k = [x_1, x_2, \dots, x_{M_k}]$ where the in-phase and quadrature components, each are made of independent pulse amplitude

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Fig. 1. Composite signal constellation diagram for 2-user CSMA with 16-QAM constituent modulations ($M_1 = M_2 = 16$) and unequal power allocation of $\alpha_1 = 0.85$ and $\alpha_2 = 0.15$. Normalized minimum distance of the composite signal $d_{min} = 0.0932$.

modulated signals that are evenly spaced for square constellations as follows:

$$i_k(n_k) = (2n_k - 1)C_k, n_k = -\frac{\sqrt{M_k}}{2} + 1, \dots, \frac{\sqrt{M_k}}{2}, \quad (3)$$

$$q_k(n_k) = (2n_k - 1)C_k, n_k = -\frac{\sqrt{M_k}}{2} + 1, \dots, \frac{\sqrt{M_k}}{2}. \quad (4)$$

The modulated symbols are then multiplied by the modulation specific scaling factor C_k and user specific power allocation α_k to ensure unity expected energy $\mathbb{E}\{|x|^2\} = 1$ of composite signal. This will ensure that the CSMA composite signals maintain the same average and peak power constraints as in single-user case. The BS shares α_k, M_k over control channels. The C_k value is calculated as follows:

$$C_k = \sqrt{\frac{3\alpha_k P_t}{2(M_k - 1)}}. \quad (5)$$

The signal at the receiver of user k can be written as:

$$r_k = g_k s + z_k, \quad (6)$$

where g_k represents baseband model of complex fading channel between the BS and user k . With this model we can safely remove pathloss parameters to focus study on interference mitigation aspects while still accounting for short-term fading effects. We assume independent Rayleigh distribution for fading channels with $\mathcal{CN}(0, 1)$. Finally, z_k represents the additive white Gaussian noise (AWGN) component with $\mathcal{CN}(0, N_0)$.

III. PROPOSED CSMA RECEIVER DESIGN

In the following, we first highlight the features of NOMA SIC method first to compare and contrast with our collaborative receiver.

A. Existing NOMA SIC Receivers

The SIC method works on the principle that the users that are closer to the BS achieve higher SNR compared with users that are further away. Hence a receiver for user l can readily decode the data sent to far users $l + 1, \dots, K$, then use the estimated data $\hat{x}_{l+1}, \dots, \hat{x}_K$ to regenerate their interference and subtract the sum from the total received signal r_l in the SIC process, to form a more reliable estimate $\hat{x}_l$ as follows:

$$\hat{x}_l = \arg \min_{x_l \in \mathbb{X}_l} \left| r_l - \sum_{k=l+1}^K \hat{h}_k \sqrt{\alpha_k P_t} \hat{x}_k - \hat{h}_l \sqrt{\alpha_l P_t} x_l \right|^2. \quad (7)$$

Usually the near users are allocated lower power e.g. $\alpha_1 < \alpha_K$. Therefore the user K that is located furthest from the BS, is allocated the highest fraction of the total power α_K . This receiver simply decodes the user's data by treating other users' data as AWGN, which reduces to performing single-user detection over M_K possibilities as follows:

$$\hat{x}_K = \arg \min_{x_K \in \mathbb{X}_K} \left| r_K - \hat{h}_K \sqrt{\alpha_K P_t} x_K \right|^2. \quad (8)$$

For the SIC to work satisfactorily, a strict power allocation condition of users must be met [5], [6]. For the case of $K = 2$, assuming user 2 has worse channel than user 1, the power allocation rule is given in [6] as follows:

$$\alpha_2 > \frac{(M_1 - 1)(\sqrt{M_2} - 1)^2}{M_2 - 1 + (M_1 - 1)(\sqrt{M_2} - 1)^2}, \quad (9)$$

while $\alpha_1 = 1 - \alpha_2$.

B. Proposed CSMA Receiver

In the proposed CSMA approach, each receiver extracts data of the desired user $\hat{x}_k$ as well as other users $x_i, i = 1, 2, \dots, K, i \neq k$ jointly from r_k by comparing r_k against composite signal from all possible transmitted data combinations $\mathbb{X}_i, i = 1, 2, \dots, K$ to identify the desired data $\hat{x}_k$ as follows:

$$\hat{x}_k = \arg \min_{x_1 \in \mathbb{X}_1, \dots, x_K \in \mathbb{X}_K} \left| r_k - \hat{h}_k \sum_{i=1}^K \sqrt{\alpha_i P_t} x_i \right|^2. \quad (10)$$

With the above detection method, the receiver is able to separate users' data as long as their possible composite signals are not identical. Note that the proposed receiver requires $\prod_{k=1}^K M_k$ computations per symbol period which is normally higher than SIC. However for the practical SNR ranges and K and M_k normally being small, this is still affordable. See Table I for an example for $K = 3$ and $\{M_1, M_2, M_3\} = \{4, 4, 4\}$.

IV. MINIMUM DISTANCE AND SER ANALYSES

It is known from [11] that SER of single user M-QAM serves as lower bound on SERs for any multiuser systems, which also applies to CSMA. For deriving the upper bound, we make use of a normalised squared minimum distance $\bar{d}_C^2$ as a metric to quantify its effect on SER of the proposed receiver so we can plug it into our analysis later. An example of d_{min} among all nearest neighbors is shown in Figure 1 for $K = 2$ and $M_1 = M_2 = 16, \alpha_1 = 0.85, \alpha_2 = 0.15$. The $\bar{d}_C^2$ is

obtained by selecting the minimum of all calculated distances as follows:

$$\bar{d}_C^2 = \min \left\{ d_{a,b}^2 \right\}, \forall a, \forall b, a \neq b, \quad (11)$$

where $d_{a,b}^2$ are the calculated distances against an array of all possible K user data combinations of size $\prod_k^K M_k$ against all other $\prod_k^M M_k - 1$ possibilities.

$$d_{a,b}^2 = \left| \sum_{k=1}^K \alpha_k P_t x_k^a - \sum_{k=1}^K \alpha_k P_t x_k^b \right|^2, a \neq b, \\ x_k^a \in \mathbb{X} = \left\{ [x_1^1, x_2^1, \dots, x_K^1] [x_1^2, x_2^1, \dots, x_K^1] \dots [x_K^{M_1}, x_2^{M_2}, \dots, x_K^{M_K}] \right\}; \\ x_k^b \in \mathbb{X} = \left\{ [x_1^1, x_2^1, \dots, x_K^1] [x_1^2, x_2^1, \dots, x_K^1] \dots [x_K^{M_1}, x_2^{M_2}, \dots, x_K^{M_K}] \right\}. \quad (12)$$

To compare and build upon the single-user case, we obtain comparable minimum distance value for a square M-QAM modulated symbols [11] of alphabet size $M_\Sigma = \prod_{k=1}^K M_k$ that can be used as a reference super-constellation, as follows:

$$\bar{d}_{M_\Sigma}^2 = \frac{6}{M_\Sigma - 1}. \quad (13)$$

Therefore the SER of CSMA can be obtained by utilizing the $\bar{d}_C^2$ in relation to $\bar{d}_{M_\Sigma}^2$ to produce a a weighted E_b/N_0 for CSMA γ_C^b , as follows:

$$\gamma_C^b = \frac{\bar{d}_C^2}{\bar{d}_{M_\Sigma}^2} \frac{\gamma}{\log_2 M_\Sigma}, \quad (14)$$

where $\gamma = \frac{P_t}{N_0}$ is the total SNR. The γ_C^b derived here can be seen as having an effect of shifting the SNR axis for CSMA by $\frac{\bar{d}_C^2}{\bar{d}_{M_\Sigma}^2}$ while keeping the same SER trend of a single user detection as long as $\bar{d}_C^2 > 0$. A probability of making a symbol error for CSMA can be then obtained after doing some manipulations on the expressions given [8] while using γ_C^b instead of γ as follows:

$$Pe_C = \frac{\sqrt{M_\Sigma} - 1}{M_\Sigma} \left\{ (\sqrt{M_\Sigma} - 1) + 4 \binom{1 - \mu_C}{2} - (\sqrt{M_\Sigma} - 1) \left\{ \frac{4}{\pi} \mu_C \tan^{-1}(\mu_C) \right\} \right\}, \quad (15)$$

where $\mu_C = \sqrt{\frac{\beta}{1 + \beta \gamma_C^b}}$ with $\beta = \frac{3 \log 2(M_\Sigma)}{2(M_\Sigma - 1)}$. Since Pe_C in (15) uses the minimum distance measure, it is expected that SER obtained from numerical simulations will be upper bounded by Pe_C ; tightness of which depends of the distribution of distance values.

V. NUMERICAL RESULTS AND DISCUSSIONS

For further analysis and comparisons with NOMA, we use simulations assuming the following setup. We use two-user system for clarity and ease of comparisons, $M_k \in \{4, 16\}$ and vary $\alpha_1 \in [0.05 - 0.5]$ where $\alpha_2 = 1 - \alpha_1$. Channel estimation is assumed perfect $\hat{g}_k = g_k, \forall k$.

TABLE I
EXAMPLE OF COMPUTATIONAL EFFORTS OF CSMA AGAINST NOMA

Scheme	Detection and Demodulation	Operations
NOMA SIC [1]	$2M_3 + 2M_2 + M_1$	20
CSMA	$M_1 M_2 M_3$	64

TABLE II
NORMALIZED SQUARED MINIMUM DISTANCES $\bar{d}_C^2$, OF CSMA FOR $K = 2$ AND DIFFERENT M_k AND α_k VALUES. AS REFERENCE, SINGLE USER SQUARE MQAM SYMBOLS WITH $M_\Sigma = 4, 16, 64, 256$ GIVE $\bar{d}_\Sigma^2$ OF 2, 0.4, 0.0952, 0.0235, RESPECTIVELY

M_1, M_2	α_1, α_2	α_1, α_2	α_1, α_2	α_1, α_2	α_1, α_2
a) 4, 4	0.15, 0.85	0.2, 0.8	0.3, 0.7	0.4, 0.6	0.5, 0.5
$\bar{d}_C^2$	0.3	0.4	0.17	0.04	0
b) 4, 16	0.15, 0.85	0.2, 0.8	0.3, 0.7	0.4, 0.6	0.5, 0.5
$\bar{d}_C^2$	0.0013	0.0045	0.0062	0.0073	0.011
c) 16, 4	0.15, 0.85	0.2, 0.8	0.3, 0.7	0.4, 0.6	0.5, 0.5
$\bar{d}_C^2$	0.06	0.08	0.02	0.010	0.011
d) 16, 16	0.15, 0.85	0.2, 0.8	0.3, 0.7	0.4, 0.6	0.5, 0.5
$\bar{d}_C^2$	0.0087	0	0.0004	0.0235	0

In Table II, we populate $\bar{d}_C^2$ values for different α_1, α_2 for the combinations a) $M_1 = 4, M_2 = 4$, b) $M_1 = 4, M_2 = 16$, c) $M_1 = 16, M_2 = 4$ and d) $M_1 = 16, M_2 = 16$. For the case of a) $M_1 = 4, M_2 = 4$, the best $\bar{d}_C^2$ is obtained for $\alpha_1 = 0.2, \alpha_2 = 0.8$ which is also the $\bar{d}_{M_\Sigma}^2$ of 16-QAM. The $\bar{d}_C^2$ reduced to 0 when $\alpha_1 = 0.5, \alpha_2 = 0.5$ as some of the composite signals become identical, resulting in detection ambiguity. The $\bar{d}_C^2$ values for b) $M_1 = 4, M_2 = 16$, are worse than that of c) $M_1 = 16, M_2 = 4$ for all cases of α_1, α_2 , except for $\alpha_1 = 0.5, \alpha_2 = 0.5$. This is because, a subset of neighbouring signal points become spaced much closer to each other in the former than in the latter case. Conversely, the combination c) $M_1 = 16, M_2 = 4$ can achieve up to $\bar{d}_C^2 = 0.08$ which is very close to $\bar{d}_{M_\Sigma}^2 = 0.0952$ of 64-QAM. Finally, $\bar{d}_C^2$ for d) $M_1 = 16, M_2 = 16$ are given, where the best $\bar{d}_C^2$ is obtained for $\alpha_1 = 0.4, \alpha_2 = 0.6$.

Figure 2 shows the SER of CSMA for $K = 2$ and $M_1 = 16, M_2 = 4$, with two users labeled as U1 and U2, respectively for different α_1, α_2 values and how they compare against NOMA under the same total SNR, P_t/N_0 . The SER upper bounds calculated using (15) are also plotted. The SER curves for U1 with $\alpha_1 = 0.17$ and U2 with $\alpha_2 = 0.83$ are the same for both NOMA and CSMA. This is because with the $\alpha_2 = 0.83$, the condition in (9) is satisfied and SIC can detect and cancel all interference fully. This indicates CSMA and NOMA achieve identical SERs when composite signals are fully separated. The SER of U2—which is allocated more power—is better than U1 as expected. The CSMA SER upper bounds obtained from (15) are plotted to show how tight these upper bounds are. The Pe_C curve for $\alpha_1/\alpha_2 = 0.17/0.83$ matches the simulated SER very well, indicating that distances are evenly distributed around $\bar{d}_C^2$. The Pe_C for $\alpha_1/\alpha_2 = 0.3/0.7$ are higher than that of simulated SERs. This can be attributed to the uneven distribution of distances with more points giving distances greater than $\bar{d}_C^2$. It is worth noting that the SER performance of CSMA depends only on how closely spaced all the possible composite signals

Fig. 2. SER of users U1 and U2 for CSMA compared with NOMA for $K = 2$, for $M_1 = 16$, $M_2 = 4$ and different α_1 , α_2 values.

Fig. 3. SER of users U1 and U2 for CSMA compared with NOMA for $K = 2$, for $M_1 = 16$, $M_2 = 16$ and different α_1 , α_2 values.

of users' are relative to each other and the magnitude of fading channels as there is no interference term as in NOMA. Therefore CSMA can operate without exhibiting error floor for $\alpha_1 = 0.3$ and $\alpha_2 = 7$ as it can identify users' data even if the composite signals cross the boundaries of fixed partitions unlike NOMA SIC.

Figure 3 shows the SER of CSMA for $K = 2$ and $M_1 = 16$, $M_2 = 16$, with two users labeled as U1 and U2, respectively for different α_1 , α_2 values and how they compare against NOMA under the same total SNR, P_t/N_0 . The SER upper bounds calculated using (15) are also plotted. Similar conclusions to that in Figure 2 can be made here. The bound Pe_C for $\alpha_1/\alpha_2 = 0.15/0.85$ show higher SER than simulated SER but the gap is less. This can be attributed to higher concentration of $d_{a,b}^2$ that are closer to $\bar{d}_C^2$ than in the previous case.

In Figure 4, we plot the simulated SERs of CSMA for a) $M_1 = 16$, $M_2 = 4$, b) $M_1 = 16$, $M_2 = 16$, for α_1 values between $[0.05 - 0.5]$ to compare its robustness against NOMA under the same conditions. It is clear that CSMA offers much better SER than NOMA, specially when $\alpha_1 \rightarrow \alpha_2$. This is because, as more composite signals from the constellation points cross the fixed boundaries NOMA cannot distinguish the desired and other user data and hence fails to show satisfactory SERs. CSMA on the contrary can separate the users' data well even when they are allocated equal powers i.e. $\alpha_1 = \alpha_2 = 0.5$ for $M_1 = 16$, $M_2 = 4$ and almost equal e.g. $\alpha_1 = 0.4$, $\alpha_2 = 0.6$ for the case of $M_1 = 16$, $M_2 = 16$ as $\bar{d}_C^2 > 0$ in both cases. CSMA performance degrades for a few α_1 values e.g. 0.1, 0.2, 0.35 as $\bar{d}_C^2 \rightarrow 0$. In such cases, SER can be improved by rotating phase of users' symbols. For example, for $M_1 = M_2 = 16$ and $\alpha_1 = 0.2$, $\alpha_2 = 0.8$

Fig. 4. SER performances of CSMA for users U1 and U2 compared with that of NOMA for a) $M_1 = 16$, $M_2 = 4$, $P_t/N_0 = 40$ dB (solid lines), and b) $M_1 = 16$, $M_2 = 16$, $P_t/N_0 = 50$ dB (dashed lines), for different α_1 within the range $[0.05 - 0.5]$ where $\alpha_2 = 1 - \alpha_1$.

as in Table II, an improved $\bar{d}_C^2 = 0.0123$ can be achieved by shifting phase of user 1 by $\pi/16$ degrees.

VI. CONCLUSIONS

We proposed a novel CSMA approach that is much more robust than NOMA in practical wireless environments and hence suitable for diverse applications. It is shown to be able separate users' data even under extreme interference conditions to relax the requirement on grouping of users and depend less on their propagation channel disparity that is a must for NOMA. In terms of throughput, it can simultaneously support e.g. two users over much wider power ranges to give sum rate of 8 bps/Hz at a SER of $1e-2$ where the NOMA operation range is very small. We have demonstrated the proof of concept of the proposed technique utilizing single antennas and standard M-QAM constellations. However, system performance could be easily improved by integrating phase rotation and standard MIMO techniques. This is the subject for future work.

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