Delay Minimization for Hybrid BAC-NOMA Offloading in MEC Networks

Haodong Li

Abstract

This paper studies the offloading service improvement of multi-access edge computing (MEC) based on backscatter communication (BackCom) assisted non-orthogonal multiple access (BAC-NOMA). A hybrid BAC-NOMA protocol is proposed, where the uplink users backscatter their tasks by leveraging the downlink signal, and then the remaining data is transmitted through uplink NOMA. In particular, a resource allocation problem is formulated to minimize the offloading delay of uplink users. The non-convex problem is transformed into a convex problem, and an iterative algorithm is developed accordingly. Simulation results show that the proposed protocol outperforms the benchmark in terms of offloading delay.

Index Terms

multi-access edge computing, non-orthogonal multiple access, backscatter communication, delay minimization.

I. INTRODUCTION

Multi-access edge computing (MEC) has been recognized as an essential technology in the envision of sixth-generation (6G) mobile network, where powerful servers are deployed at the edge of the based station (BS) [1], [2]. Hence, mobile devices are encouraged to offload their computational intensive tasks to the edge server and then obtain the processed results. The MEC offloading demands significant communication service improvement to accommodate the large traffic volume, and recent works show that the combination of non-orthogonal multiple access (NOMA) and MEC can significantly improve the spectrum efficiency and reduce the latency [3], [4]. Moreover, backscatter communication (BackCom) can prolong the lifetime of energy constrained mobile devices, where other signals can be used to excite the circuit of the BackCom device (BD) [5]–[7]. Therefore, the combination of BackCom and NOMA (BAC-NOMA) is considered to efficiently improve the offloading service of the resource limited devices.
In previous works, a few BAC-NOMA protocols have been applied to improve MEC offloading performance. For instance, the authors in [6] proposed a BAC-NOMA scheme, where the NOMA users receive the signals from both the BS and the BD that excited by the downlink transmission. The full-duplex (FD) BAC-NOMA scheme was considered in [5], where the downlink transmission was used to excite the circuit of BDs to perform uplink transmission to the BS. The uplink sum rate maximization problem was studied and the optimal solution was obtained by reformulating the problem as a linear programming problem.

Different from the existing works which mainly focus on the EE maximization [6] and sum rate maximization [5], [8] of BAC-NOMA schemes, this paper considers the delay minimization problem of a hybrid BAC-NOMA assisted MEC offloading scenario. In particular, the signal of the downlink transmission can excite the circuit of BDs to upload the tasks to the MEC server. Since the existence of FD interference, those BDs may not be able to finish offloading when the downlink transmission is active. Therefore, a second time duration is scheduled to continue the offloading by using the NOMA uplink transmission. By applying the Dinkelbach method and quadratic transformation, an iterative based algorithm is proposed to obtain the sub-optimal solution to the original non-convex problem. By comparing with benchmarks, simulation results demonstrate that the proposed protocol can significantly reduce the offloading latency.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

Consider a BS equipped with an MEC server to serve one downlink user $U_0$ and $k$ uplink BDs which is denoted by $BD_k$, where $k \in \{1, \ldots, K\}$. Assume that during the time slot $t_0$, the BS starts the transmission to $U_0$. The downlink transmit power is denoted by $P_0$, and the received signal at $BD_k$ can be expressed as $\sqrt{P_0} h_k s_0$, where $h_k$ is the channel gain between the BS and $BD_k$, and $s_0$ represents the downlink signal to $U_0$ with unit power. By leveraging the BackCom protocol, the downlink signal can excite the circuits of those BDs, and the reflected signal from $BD_k$ can be expressed as $\sqrt{\eta_k P_0} h_k s_0 s_k$ where $\eta_k \in [0,1]$ is the BackCom reflection coefficient, and $s_k$ denotes the signal of $BD_k$ with unit power. Therefore, the received reflected signal at the BS can be represented by [5]:

$$y_{BS} = \sum_{k=1}^{K} \sqrt{\eta_k P_0 h_k^2 s_0 s_k} + I_{SI} + n_{BS}, \quad (1)$$
where $I_{SI}$ represents the FD self-interference, which is assumed to be complex Gaussian distributed, and it satisfies $I_{SI} \sim \mathcal{CN}(0, \alpha P_0 |h_{SI}|^2)$, and $\alpha \in [0, 1]$ represents the amount of residual interference. The complex additive white Gaussian noise (AWGN) at the receiver is denoted by $n_{BS} \sim \mathcal{CN}(0, \sigma^2)$ with zero mean and variance $\sigma^2$.

Without loss of generality, the BDs are arranged in a descending order of the effective channels. The successive interference cancellation (SIC) technique is adopted for NOMA decoding, in which the BS decodes the signals of BDs with better channel gains priorly and treats the signals of the BDs with worse channel gains as interference. By assuming the downlink signal $s_0$ is perfectly known by the BS, the achievable rate of BD$_k$ can be expressed as

$$r_{b,k} = B \log_2 \left( 1 + \frac{\eta_k P_0 |h_k|^4 |s_0|^2}{\sum_{j=k+1}^K \eta_j P_0 |h_j|^4 |s_0|^2 + \alpha P_0 |h_{SI}|^2 + \sigma^2} \right),$$

where $0 \leq \alpha \ll 1$ denotes the amount of FD residual self-interference [5]. Moreover, since the characteristics of BackCom transmission, the reflected signals from the BDs will introduce extra interference to the downlink user, and the received signal at $U_0$ can be written as [5]:

$$y_0 = \sqrt{P_0} h_0 s_0 + \sum_{k=1}^K \sqrt{\eta_k P_0 g_k h_k s_k} + n_{U_0},$$

where $h_0$ is the channel gain between the BS and $U_0$, $g_k$ represents the channel gain between $U_0$ and BD$_k$, and $n_{U_0} \sim \mathcal{CN}(0, \sigma^2)$ denotes the AWGN between $U_0$ and the BS. Hence, the achievable rate for $U_0$ is

$$r_0 = B \log_2 \left( 1 + \frac{P_0 |h_0|^2}{\sum_{k=1}^K \eta_k P_0 |g_k|^2 |h_k|^2 + \sigma^2} \right).$$

On top of the BackCom transmission, this paper also considers the active uplink transmission scheme, in which an extra time duration can be designated for BDs’ uplink transmission. It is assumed that the offloading may not be able to finish within $t_0$. Forcing the BDs to finish offloading within $t_0$ could require a higher downlink power $P_0$ or a longer transmission time $t_0$, which may degrade the transmission service of $U_0$. Instead, an additional time duration $t_a$ can be utilized by the BDs to perform NOMA uplink transmission. The achievable active transmission rate for BD$_k$ can be expressed as

$$r_{a,k} = B \log_2 \left( 1 + \frac{p_{a,k} |h_k|^2}{\sum_{j=k+1}^K p_{a,j} |h_j|^2 + \sigma^2} \right),$$

where $p_{a,k}$ denotes the active transmission power of BD$_k$. 
B. Problem Formulation

The aim of this paper is to minimize the MEC offloading delay of $K$ BDs. The offloading delay is defined as $T = t_0 + t_a$, where $t_0$ is assumed to be fixed and predetermined by the BS since it is primarily assigned to the downlink transmission for $U_0$. Consider $K$ BDs offload tasks to the MEC server through NOMA simultaneously, the time consumption $t_a$ for offloading the remaining data can be calculated as

$$t_a = \frac{L_k - t_0 r_{b,k}}{r_{a,k}} , k \in \{1, ..., K\} .$$

(6)

where $L_k$ is the offloading data amount of BD$_k$. Hence, based on the expression of $t_a$, the delay minimization problem can be formulated as

$$\text{(P1)} \begin{array}{rl}
\min_{P_0, p_a, \eta} & t_0 + t_a \\
\text{s.t.} & r_0 \geq \gamma_0 , \\
& 0 \leq t_a p_{a,k} \leq E_{k,\text{max}}, \forall k \\
& 0 \leq p_{a,k} \leq P_{a,\text{max}}, \forall k \\
& 0 \leq P_0 \leq P_{0,\text{max}} , \\
& 0 \leq \eta_k \leq 1, \forall k \\
\end{array}$$

(7a)

(7b)

(7c)

(7d)

(7e)

(7f)

where $p_a \triangleq [p_{a,1}, p_{a,2}, ..., p_{a,k}]$, and $\eta \triangleq [\eta_1, \eta_2, ..., \eta_K]$. The minimum achievable rate for the downlink transmission is guaranteed by (7b). Constraint (7c) ensures that the energy consumption for offloading is limited by the amount of energy of each BD. The power of uplink transmission for BD$_k$ is limited in (7d). Constraint (7e) guarantees the range of the downlink transmission power, and (7f) limits the range of the reflection coefficient. Since (P1) is non-convex due to the fractional form of the objective function and coupled variables, a convex equivalent of this problem is developed to tackle the resource allocation problem in the next section.

III. PROBLEM TRANSFORMATION AND SOLUTION

In this section, the paper proposes two approaches to transform the original non-convex problem into two equivalent convex forms in order to adapt the two different offloading scenarios, i.e., pure BAC-NOMA offloading and hybrid BAC-NOMA offloading. If BDs are able to finish offloading within $t_0$, the pure BAC-NOMA scheme becomes feasible, and the second time
duration \( t_a = 0 \). Otherwise, the hybrid BAC-NOMA scheme is adopted. Based on the above two schemes, an iterative based algorithm is proposed to obtain the resource allocation efficiently.

**Lemma 1.** Define \( \overline{L} = \sum_{k=1}^{K} L_k \), \( t_a \) is equivalent to the following expression:

\[
\beta_a = \frac{\overline{L} - t_0 R_b}{R_a},
\]

(8)

where \( R_b^b = \sum_{k=1}^{K} r_{b,k} \) and \( R_a^a = \sum_{k=1}^{K} r_{a,k} \).

**Proof.** First, the remaining data after the first time duration \( t_0 \) is denoted as \( \beta_a,k = L_k - t_0 r_{b,k} \). As all BDs finish offloading their tasks simultaneously within the same transmission time \( t_a \), the following relation holds:

\[
\frac{\beta_a,1}{r_{a,1}} = \frac{\beta_a,2}{r_{a,2}} = \ldots = \frac{\beta_a,K}{r_{a,K}}
\]

(9)

Since \( \frac{\beta_a,1}{r_{a,1}} = \frac{\beta_a,K}{r_{a,K}} \), it can be found that \( \epsilon_k \triangleq \frac{\beta_a,k}{\beta_a,1} = \frac{r_{b,k}}{r_{a,1}} \). Then, the following fraction can be constructed by multiplying the same term with both numerator and the denominator:

\[
\frac{\beta_a,1}{r_{a,1}} = \frac{\beta_a,1 (1 + \epsilon_2 + \epsilon_3 + \ldots + \epsilon_K)}{r_{a,1} (1 + \epsilon_2 + \epsilon_3 + \ldots + \epsilon_K)}.
\]

(10)

Therefore, the above equation can be written as

\[
\frac{\beta_a,1}{r_{a,1}} = \frac{\sum_{k=1}^{K} \beta_a,k}{r_{a,1} (1 + \epsilon_2 + \epsilon_3 + \ldots + \epsilon_K)}
\]

(11)

and the transmission time \( t_a \) can be written as

\[
\frac{\beta_a,1}{r_{a,1}} = \frac{\sum_{k=1}^{K} (L_k - t_0 r_{b,k})}{\sum_{k=1}^{K} r_{a,k}}
\]

(12)

Based on (2), the sum rate of BD\(_K\) and BD\(_{K-1}\) is

\[
\gamma_{b,K} + \gamma_{b,K-1} = B \log_2 \left( 1 + \frac{\eta_{K-1} P_0 |h_{K-1}|^4 |s_0|^2 + \eta_{K} P_0 |h_{K}|^4 |s_0|^2}{\alpha P_0 |h_{SI}|^2 + \sigma^2} \right).
\]

(13)

Similarly, it can be found that the sum rate of

\[
\gamma_{b,K-2} + \gamma_{b,K-1} + \gamma_{b,K} =
\]

\[
B \log_2 \left( 1 + \frac{\sum_{i=K-2}^{K} \eta_i P_0 |h_i|^4 |s_0|^2}{\alpha P_0 |h_{SI}|^2 + \sigma^2} \right).
\]

(14)
Therefore, by repeating the above manipulations, the sum rate of $K$ BDs using the backscatter transmission can be written as
\[ R_b = \sum_{k=1}^{K} r_{b,k} = B \log_2 \left( 1 + \sum_{k=1}^{K} \frac{\eta_k P_0 \left| h_k \right|^4 \left| s_0 \right|^2}{\alpha P_0 \left| h_{SI} \right|^2 + \sigma^2} \right). \]  
(15)

Similar to (15), the sum rate for the active uplink transmission can be written as
\[ R_a = \sum_{k=1}^{K} r_{a,k} = B \log_2 \left( 1 + \sum_{k=1}^{K} \frac{p_{a,k} \left| h_k \right|^2}{\sigma^2} \right). \]  
(16)

By substituting (15) and (16) into (12), the offloading latency $t_a$ can be written as
\[ t_a = \tilde{L} - t_0 \frac{R_b R_a}{R_a}. \]

A. Pure BAC-NOMA Case

If all BDs can finish offloading within $t_0$, the second time duration $t_a$ will be zero. By assuming the back-scatter transmission satisfies the constraint $L_k = t_0 r_{b,k}$. According to Lemma 1, the above constraint is equivalent to $\tilde{L} = t_0 R_b$. Hence, the original problem becomes a feasibility problem, which can be formulated as

\[ \text{find} \quad P_0, p_{r,k} \]

\[ \text{s.t.} \quad \sum_{k=1}^{K} p_{r,k} \left| h_k \right|^4 \left| s_0 \right|^2 - \gamma \left( \alpha P_0 \left| h_{SI} \right|^2 + \sigma^2 \right) = 0, \]  
(17a)

\[ P_0 \left| h_0 \right|^2 - \tilde{\gamma}_0 \sum_{k=1}^{K} p_{r,k} \left| g_k \right|^2 \left| h_k \right|^2 - \tilde{\gamma}_0 \sigma^2 \geq 0, \]  
(17b)

\[ 0 \leq P_0 \leq P_{0,\text{max}}, \]  
(17c)

\[ 0 \leq p_{r,k} \leq P_0, \quad \forall k, \]  
(17d)

where $p_{r,k} = \eta_k P_0$, $\gamma = 2 \frac{\tilde{L}}{t_0} - 1$, and $\tilde{\gamma}_0 = 2 \frac{\gamma_0}{\mu} - 1$. It is evident that the above problem is convex and the feasibility can be found by some optimization solvers, such as CVX.

B. Hybrid BAC-NOMA Case

When $\tilde{L} \geq t_0 R_b$, which means BDs cannot finish offloading during $t_0$, and the remaining data will be offloaded during $t_a$. Since the objective function in (P1) is fractional and non-convex, the Dinkelbach method [9] is leveraged to transform the original problem into an equivalent
objective function. The principle of the Dinkelbach’s method is to convert the fractional format into the following optimization problem:

\[
\begin{align*}
\text{(P3)} & \quad \min_{P_0, p_a, \eta} & \tilde{L} - t_0 R_b - \mu R_a \\
\text{s.t.} & & 0 \leq \mu p_{a,k} \leq E_{k,\text{max}} \\
\end{align*}
\]

(18a)

where \( \mu \) is an auxiliary variable which is determined by the proposed iterative algorithm in the later section.

Problem \((P3)\) is still non-convex due to the existence of FD interference in the second term in \( R_b \). Hence, to further simplify the problem, quadratic transform \([10]\) is applied to the objective function of \((P3)\), and the reformulated problem can be expressed as

\[
\begin{align*}
\text{(P4)} & \quad F(\mu) = \tilde{L} - \mu B \log_2 \left( 1 + \frac{\sum_{k=1}^{K} p_{a,k} |h_k|^2}{\sigma^2} \right) \\
& \quad \min_{P_0, p_a, p_r} \left\{ 1 + 2y \sqrt{\sum_{k=1}^{K} p_{r,k} |h_k|^4 |s_0|^2} \right\} \\
& \quad \text{s.t.} \quad (7d), (7e), (17d), (18b)
\end{align*}
\]

(19a)

where \( y \) is an auxiliary variable which will be updated iteratively. For given \( p_{r,k} \) and \( P_0 \), based on the principle of quadratic function, the optimal \( y^* \) to minimize the objective function can be determined by

\[
y^* = \sqrt{\frac{\sum_{k=1}^{K} p_{r,k} |h_k|^4 |s_0|^2}{\alpha P_0 |h_{SI}|^2 + \sigma^2}}.
\]

(20)

Hence, for fixed auxiliary variables \( y \) and \( \mu \), problem \((P4)\) becomes a convex problem, and CVX can be utilized to solve this problem efficiently. By providing an initial feasible \( y^{(0)} \), the optimal \( P_0^*, p_{r,k}^*, \) and \( p_{a,k}^* \) can be obtained based on the given \( y^{(0)} \). Then, \( y \) can be updated for next iteration based on (20) with the obtained optimization variables.

Therefore, an algorithm is proposed to iteratively update the power allocation solution and the iterative variable \( \mu \). The procedure of this proposed scheme is summarized in Algorithm [1]. With the increment of \( l \), the Dinkelbach iterative variable \( \mu \) will finally converge to the \( \varepsilon \)-optimal \( \mu^* \), where the \( \varepsilon \)-optimal \( \mu^* \) can be achieved if \( F(\mu^*) \leq \varepsilon \). The convergence of Dinkelbach based
algorithm was proved in [9], and simulation results also show that the proposed algorithm is able to converge within a few iterations, which is presented later in the next section.

Algorithm 1 Iterative based resource allocation algorithm

1: Set $l = 0$, $\mu = +\infty$
2: if $(P_2)$ is feasible then
3: Pure backscatter transmission is adopted.
4: Solve $(P_2)$ and obtain $P_0^*$ and $p_{r,k}^*$.
5: else
6: Initialize $P_0$, $p_{r,k}$ with feasible values.
7: repeat
8: $l = l + 1$
9: Update $y^{(l)}$ by (20).
10: Solve problem $(P_4)$ with fixed $\mu$, and obtain $P_0^{(l)}$, $p_{r,k}^{(l)}$, and $p_{a,k}^{(l)}$.
11: Solve $F(\mu^{(l)})$. 
12: update $\mu$ as $\mu^{(l)} = \frac{\tilde{L}-t_0 B \log_2 \left(1+\frac{\sum_{k=1}^{K} |h_k|^4 |s_k|^2}{\sigma^2\sum_{k=1}^{K} |h_k|^2} \right)}{B \log_2 \left(1+\frac{\sum_{k=1}^{K} |h_k|^2}{\sigma^2\sum_{k=1}^{K} |h_k|^2} \right)}$.
13: until $F(\mu^{(l)}) \leq \varepsilon$.
14: $P_0^* = P_0^{(l)}$, $p_{r,k}^* = p_{r,k}^{(l)}$, and $p_{a,k}^* = p_{a,k}^{(l)}$.
15: end if

IV. Simulation Results

In this section, simulation results are presented and discussed to evaluate the proposed hybrid NOMA-BackCom scheme. The simulation settings are listed as follows. The channel gain from the BS to BD$_k$ is $h_k = \tilde{h}_k d_k^{-\chi}$, where $\tilde{h}_k$ is a Rayleigh fading channel coefficient and $d_k$ is the corresponding distance between BD$_k$ and the BS, and $\chi$ denotes the path-loss exponent which is set to 3.76 throughout the simulation. Similarly, the channel gain $h_0$ that between the BS and $U_0$, and the channel gain $g_k$ that between $U_0$ and BD$_k$ are realized in the same way, in which the distance between $U_0$ and BD$_k$ is denoted by $\tilde{d}_k$. The transmission radius of the BS is 50 m, and all BDs as well as $U_0$ are covered within the disc region. The AWGN power is $\sigma^2 = BN_0$, where $B = 5$ MHz, and $N_0 = -94$ dBm/Hz denotes the AWGN spectrum density. The error tolerance $\varepsilon = 10^{-4}$, and the simulation results are obtained after $10^3$ realizations.
The convergence performance of the proposed Algorithm 1 and the effect of amount of FD residual self-interference are demonstrated in Fig. 1. In this figure, the data length of each user $L_k$ is set to $10^6$ bits, $t_0 = 0.5$ s, and the maximum uplink transmission power $p_{a,\text{max}} = 0.5$ watt. According to the simulation results, the algorithm can efficiently converge within a few iterations. Additionally, the amount of FD residual self-interference can affect the offloading delay since the higher residual can reduce the achievable rate of each BD and hence the remaining data amount for offloading in the second duration increases.

As shown in Fig. 2, the relationship between the average offloading delay and the data length of each user is studied under the fixed QoS constraint $\gamma_0 = 2$ Mbit/s and $E_{\text{max}} = 0.1$ joules.
The pure NOMA scheme is considered as a benchmark, where BDs do not perform BackCom during $t_0$, which means that $\eta_k = 0, \forall k$. For both transmission schemes, the average delay increases with the growth of offloading data length. The dashed lines which represent the pure NOMA uplink transmission show higher average offloading delay compared to the solid line with the hybrid offloading scheme. The proposed hybrid scheme is efficient for offloading delay reduction. Moreover, the higher power budget for offloading can significantly reduce the system delay for both cases.

V. CONCLUSION

In this work, the delay minimization problem for hybrid BAC-NOMA assisted MEC network is investigated. The original delay minimization problem is non-convex. By utilizing the Dinkelbach method and quadratic transformation, the non-convex problem is equivalently reformulated into a convex form. Simulation results demonstrated the performance superiority of the proposed hybrid scheme by comparing with the pure uplink NOMA scheme in terms of average delay.

REFERENCES

[1] K. Wang, Z. Ding, D. K. C. So, and G. K. Karagiannidis, “Stackelberg game of energy consumption and latency in MEC systems with NOMA,” *IEEE Trans. Commun.*, vol. 69, no. 4, pp. 2191–2206, 2021.

[2] H. Li, F. Fang, and Z. Ding, “Joint resource allocation for hybrid NOMA-assisted MEC in 6G networks,” *Digital Communications and Networks*, vol. 6, no. 3, pp. 241–252, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352864819304274

[3] B. Liu, C. Liu, and M. Peng, “Resource allocation for energy-efficient MEC in NOMA-enabled massive iot networks,” *IEEE J. Sel. Areas Commun.*, vol. 39, no. 4, pp. 1015–1027, 2021.

[4] F. Fang, Y. Xu, Z. Ding, C. Shen, M. Peng, and G. K. Karagiannidis, “Optimal resource allocation for delay minimization in NOMA-MEC networks,” *IEEE Trans. Commun.*, vol. 68, no. 12, pp. 7867–7881, 2020.

[5] Z. Ding and H. V. Poor, “On the application of BAC-NOMA to 6G umMTC,” *IEEE Commun. Lett.*, vol. 25, no. 8, pp. 2678–2682, 2021.

[6] Y. Xu, Z. Qin, G. Gui, H. Gacanin, H. Sari, and F. Adachi, “Energy efficiency maximization in NOMA enabled backscatter communications with QoS guarantee,” *IEEE Wireless Commun. Lett.*, vol. 10, no. 2, pp. 353–357, 2021.

[7] Y. Xu, B. Gu, R. Q. Hu, D. Li, and H. Zhang, “Joint computation offloading and radio resource allocation in MEC-based wireless-powered backscatter communication networks,” *IEEE Trans. Veh. Technol.*, vol. 70, no. 6, pp. 6200–6205, 2021.

[8] G. Yang, X. Xu, and Y.-C. Liang, “Resource allocation in NOMA-enhanced backscatter communication networks for wireless powered IoT,” *IEEE Wireless Commun. Lett.*, vol. 9, no. 1, pp. 117–120, 2020.

[9] W. Dinkelbach, “On nonlinear fractional programming,” *Manage. Sci.*, vol. 13, no. 7, pp. 492–498, mar 1967. [Online]. Available: https://doi.org/10.1287/mnsc.13.7.492

[10] K. Shen and W. Yu, “Fractional programming for communication systems—part I: Power control and beamforming,” *IEEE Trans. Signal Process.*, vol. 66, no. 10, pp. 2616–2630, 2018.