OPTIMAL RESOURCE ALLOCATION FOR MULTIPLE ACCESS CHANNEL WITH CONFERENCING LINKS AND A SHARED RENEWABLE ENERGY SOURCE

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ABSTRACT

This paper investigates the optimal resource allocation for the Gaussian multiple access channel (MAC) with conferencing links, where the two transmitters could talk to each other via some wired rate-limited channels. Moreover, the two transmitters are assumed to be powered by a shared energy harvester, and a deterministic energy-harvesting (EH) model is adopted by assuming that the energy arrival times and the corresponding harvested amounts are non-causally known prior to transmissions. We formulate a continuous-time power allocation problem to characterize the maximum departure region over a finite time horizon. By exploiting its convexity, this problem is simplified as a discrete-time problem and the optimal solution is obtained. In particular, it is shown that there exists a certain maximum possible transmission rate (the capping rate) at one of the transmitters. Finally, we compare the performance of the optimal offline algorithm against that of the online one.

Index Terms— Multiple access channel, conferencing links, energy harvesting, maximum departure region.

1. INTRODUCTION

Energy harvesters own the capability to capture energy from the environment and mitigate the unsustainability problem for the conventional constant power suppliers, e.g., batteries. It is envisioned as one of the important components in the future national infrastructure, such as in smart grid and wireless sensor networks (WSNs). However, the energy provided by energy harvester is fluctuating and varying over time, which requires advanced power control and scheduling schemes [1, 2, 3].

The single-user communication systems powered by an energy harvester with a deterministic EH model have been investigated in [1], for which the energy information is non-causally known prior to transmissions, and with random EH models in [2], for which the energy information is only causally known to the transmitter. Regarding multiuser communication systems, offline or online algorithms to characterize the maximum departure region were considered for the broadcast channel (BC) [4, 5], the multiple access channel (MAC) [6], and the interference channel [7], respectively. It is worth noting that for the MAC, no systematic results were provided in [6].

In this paper, we study the two-transmitter Gaussian MAC with conferencing links, where the two transmitters share one EH source. The model with both shared information and energy supply is suitable for practical scenarios where certain wired connections exist between the two transmitters. We adopt the deterministic EH model by assuming that the energy information can be predicted with acceptable accuracy. We characterize the boundary of the maximum departure region by solving a power allocation problem to maximize the weighted sum transmitted bits from the two transmitters. We provide the structure of the optimal power allocation and show that there is a capping rate at one of the transmitters which is the maximum value of the transmission rate for this user.

Notation: $(x)^+ = \max(0, x)$; $\mathcal{C}(x) = \log_2(1 + x)$.

2. SYSTEM MODEL AND PROBLEM FORMULATION

2.1. System Model

We consider a two-transmitter Gaussian MAC where the two transmitters are connected by certain wired rate-limited two-way conferencing links. Via the conferencing links, transmitter 1 can talk to transmitter 2 with a rate up to C_{12}, similar for the opposite direction with a rate up to C_{21}. Moreover, it is assumed that the two transmitters share one common EH source with an infinite battery capacity (the energy sharing could be enabled via the wired conferencing links), and we will leave the finite battery capacity case for future study. The constant channel power gains from transmitter 1 and transmitter 2 to the receiver are denoted by h_1 and h_2, respectively. Without loss of generality, we assume $h_1 > h_2$, which indicates that the transmitter 1 link is stronger than the transmitter 2 link[1].

[1]The optimal resouce allocation for the case $h_1 = h_2$ can be obtained with similar analysis, and thus is omitted here due to the space limitation.

It is assumed that the additive noise at the receiver is circularly symmetric complex Gaussian (CSCG), with zero mean and unit variance.

We adopt a deterministic EH model, which assumes that the energy arrival times and the corresponding harvested amounts are known prior to transmissions. Within the considered time period $[0, T)$, suppose there are N energy arrivals with the n-th harvested energy amount denoted as E_n and arriving at time s_n, $n = 0, 1, \cdots, N-1$. In particular, we set $s_0 = 0$. The duration between the $(n-1)$-th and the n-th energy arrivals is denoted as $l_n = s_n - s_{n-1}$, $1 \le n \le N$, with $s_N = T$ for convenience. Denote the data rate and the corresponding transmission power for transmitter i, $i = 1, 2$, at time t as $r_i(t)$ and $P_i(t)$, respectively.

2.2. Problem Formulation

In this subsection, we first consider a sum power minimization problem and derive the function $g(r_1(t), r_2(t))$, which is the minimum sum power to achieve a given rate pair $r_1(t)$ and $r_2(t)$ across the two users at time t. Then, we rigorously define the maximum departure region and formulate a continuous-time power allocation problem to characterize the departure region boundary. In the sequel, we omit the index t whenever it causes no confusion.

For the MAC with conferencing links, the coding scheme is described as follows. Transmitter i, $i = 1, 2$, splits its message w_i, into two sub-messages w_i^c and w_i^p: w_i^c is sent to its counterpart via the conferencing link to form a common message and w_i^p is directly sent to the receiver. As a result of conferencing, each transmitter has a common message $w^c = (w_1^c, w_2^c)$ and a private message w_i^p, $i = 1, 2$, which are allocated with the power P_i^c and $P_i^p = P_i - P_i^c$, respectively. With the above coding scheme, the capacity region of the MAC with conferencing is given as [8]

$$\begin{cases} (r_1 - C_{12})^+ \le \mathcal{C}(h_1 P_1^p) & (1)\\ (r_2 - C_{21})^+ \le \mathcal{C}(h_2 P_2^p) & (2)\\ (r_1 - C_{12})^+ + (r_2 - C_{21})^+ \le \mathcal{C}(h_1 P_1^p + h_2 P_2^p) & (3)\\ r_1 + r_2 \le \mathcal{C}\left(h_1 P_1 + h_2 P_2 + 2\sqrt{h_1 P_1^c h_2 P_2^c}\right). & (4) \end{cases}$$

It is worth noting that the capacity region defined by (1)-(4) is convex over (r_1, r_2) [9].

Then, the sum power function $g(r_1, r_2)$ can be obtained by solving the following sum power minimization problem:

$$\text{(P1)} \;\; g(r_1, r_2) = \min_{P_1^c, P_1^p, P_2^c, P_2^p} P_1^c + P_1^p + P_2^c + P_2^p \quad (5)$$

$$\text{s.t. } (1)-(4),\ P_1^c \ge 0,\ P_1^p \ge 0,\ P_2^c \ge 0,\ P_2^p \ge 0. \quad (6)$$

It can be shown that problem (P1) is convex [9] by showing that its feasible region is convex over $(P_1^c, P_1^p, P_2^c, P_2^p)$. Since the optimization variables P_1^c and P_2^c are only restricted by constraint (4), we can prove that it is optimal to have $h_2 P_1^c = h_1 P_2^c$ [10]. Therefore, P_1^c and P_2^c can be eliminated from the problem by proper substitutions in terms of P_1^p and P_2^p. The simplified problem with only optimization variables P_1^p and P_2^p can be explicitly solved, which is summarized in the following result.

Proposition 1 *For a given rate pair (r_1, r_2), the minimum sum power $g(r_1, r_2)$ can be achieved when equalities are achieved for (2), (3), (4) and $h_2 P_1^c = h_1 P_2^c$. The minimum sum power $g(r_1, r_2)$ is then given as [10]:*

$$\begin{aligned} g(r_1, r_2) &\triangleq \frac{h_2}{h_1(h_1 + h_2)} 2^{(r_1 - C_{12})^+ + (r_2 - C_{21})^+} \\ &+ \frac{1}{h_1 + h_2} 2^{r_1 + r_2} + \left(\frac{1}{h_2} - \frac{1}{h_1}\right) 2^{(r_2 - C_{21})^+} - \frac{1}{h_2}, \end{aligned} \quad (7)$$

and the corresponding power allocation for the messages is given as:

$$P_1^{c*} = \frac{h_1\left(2^{r_1 + r_2} - 2^{(r_1 - C_{12})^+ + (r_2 - C_{21})^+}\right)}{(h_1 + h_2)^2}, \quad (8)$$

$$P_1^{p*} = \frac{1}{h_1} 2^{(r_2 - C_{21})^+}\left(2^{(r_1 - C_{12})^+} - 1\right), \quad (9)$$

$$P_2^{c*} = \frac{h_2\left(2^{r_1 + r_2} - 2^{(r_1 - C_{12})^+ + (r_2 - C_{21})^+}\right)}{(h_1 + h_2)^2}, \quad (10)$$

$$P_2^{p*} = \frac{1}{h_2}\left(2^{(r_2 - C_{21})^+} - 1\right). \quad (11)$$

Note that $g(r_1, r_2)$ given in (7) is a non-decreasing convex function jointly over r_1 and r_2. Based on (7), the causal EH constraint at time t could be modeled as:

$$\int_0^t g(r_1(\tau), r_2(\tau)) d\tau \le \sum_{n=0}^{j} E_n,\ \forall t \in [0, T), \quad (12)$$

where j is the index of the last energy arrival before time t, i.e., $j = \arg \max_{0 \le j \le N-1} \{s_j \le t\}$. Based on the above analysis, we define the maximum departure region $\mathcal{D}(T)$ as follows.

Definition 1 *Within the time period $[0, T)$, the **maximum departure region** $\mathcal{D}(T)$ of the MAC with conferencing links is defined as the union of all achievable bits pair (B_1, B_2) under the EH constraint (12), i.e.,*

$$\mathcal{D}(T) = \left\{(B_1, B_2) \mid B_i = \int_0^T r_i(t)\, dt, i = 1, 2,\ (12)\right\}, \quad (13)$$

where B_i is the total amount of transmitted data from transmitter i, $i = 1, 2$.

Since for a given $t \in [0, T)$, the capacity region given in (1)-(4) is convex, the maximum departure region $\mathcal{D}(T)$, defined as the integral over a finite time horizon $[0, T)$ in (13), still owns convexity, which is summarized as follows.

Proposition 2 *The maximum departure region $\mathcal{D}(t)$ defined in (13) for the MAC with conferencing links and the EH constraint is convex.*

Due to Proposition 2 and the special structure defined in the positive orthant for $\mathcal{D}(T)$, we can characterize its boundary by maximizing the weighted sum of B_1 and B_2 as follows.

$$\text{(P2)} \max_{\{r_1(t), r_2(t)\}} \quad \mu_1 B_1 + \mu_2 B_2 \tag{14}$$

$$\text{s.t.} \quad (12), \tag{15}$$

where $\mu_1 + \mu_2 = 1$, $\mu_1 > 0$, $\mu_2 > 0$, are the adjustable weighting factors. It is easy to observe that the problem (P2) is still convex over r_1 and r_2 [9]. By the convexity of $g(r_1, r_2)$, we can obtain the following result similar to Lemma 1 in [4]:

Lemma 1 *The optimal rate $r_i^*(t)$, $i = 1, 2$, for problem (P2) keeps constant between any two adjacent energy arrival times.*

Denote $r_i(t), t \in [s_{n-1}, s_n)$, $i = 1, 2$, as r_{in}, $n = 1, \cdots, N$. Accordingly, B_1 and B_2 defined in (13) can be rewritten as $B_1 = \sum_{n=1}^{N} r_{1n} l_n$, $B_2 = \sum_{n=1}^{N} r_{2n} l_n$. Then, problem (P2) can be simplified as a discrete-time problem as:

$$\text{(P3)} \max_{\{r_{1n}, r_{2n}\}} \quad \mu_1 \sum_{n=1}^{N} r_{1n} l_n + \mu_2 \sum_{n=1}^{N} r_{2n} l_n \tag{16}$$

$$\text{s.t.} \quad \sum_{n=1}^{j} g(r_{1n}, r_{2n}) l_n \le \sum_{n=0}^{j-1} E_n, \quad 1 \le j \le N. \tag{17}$$

3. OPTIMAL POWER AND RATE ALLOCATION

In this section, we first describe the structure of the optimal sum power allocation for problem (P3), i.e., the structure of the optimal value for $g(r_{1n}, r_{2n})$, $n = 1, \cdots, N$. Then, to completely characterize the transmission scheme, we obtain the optimal rate scheduling between the two transmitters.

By the convexity of $g(r_1, r_2)$, it can be proved [10] that the optimal sum power allocation has the same structural properties as that for the single-user channel case discussed in [1]:

$$i_k = \arg \min_{i_{k-1} < i \le N} \left\{ \frac{\sum_{j=i_{k-1}}^{i-1} E_j}{s_i - s_{i_{k-1}}} \right\}, \tag{18}$$

$$g(r_{1n}, r_{2n}) = \frac{\sum_{j=i_{k-1}}^{i_k - 1} E_j}{s_{i_k} - s_{i_{k-1}}} \doteq P_n^*, \text{for } i_{k-1} < n \le i_k \tag{19}$$

where $i_0 = 0$. The proof will be given in [10].

It is worth noting that the optimal sum power allocation obtained by (18) and (19) is only determined by the energy arrival information and is independent of μ_1 and μ_2. Therefore, solving problem (P3) is equivalent to solving the following problem (P4) for each $n \in \{1, \cdots, N\}$ individually [4].

$$\text{(P4)} \max_{r_{1n}, r_{2n}} \quad \mu_1 r_{1n} + \mu_2 r_{2n} \tag{20}$$

$$\text{s.t.} \quad g(r_{1n}, r_{2n}) = P_n^*. \tag{21}$$

Before presenting the optimal solution of problem (P4), we show some properties for the curve defined by $g(r_{1n}, r_{2n}) = P_n^*$ (denoted as $\mathcal{G}$).

1) If the point (r_{1n}, r_{2n}) on the curve $\mathcal{G}$ is in the region $\mathcal{R}_1 = \{(r_{1n}, r_{2n}) \in \mathcal{G} \mid 0 < r_{1n} < C_{12}, 0 < r_{2n} < C_{21}\}$, it can be proved [10] that $\frac{dr_{2n}}{dr_{1n}} = -1$.

2) If the point (r_{1n}, r_{2n}) on the curve $\mathcal{G}$ is in the region $\mathcal{R}_2 = \{(r_{1n}, r_{2n}) \in \mathcal{G} \mid r_{1n} > C_{12}, 0 < r_{2n} < C_{21}\}$, it can be proved [10] that

$$\frac{dr_{2n}}{dr_{1n}} = \frac{1}{-1 + \frac{h_2 2^{(r_{1n} - C_{12})}}{(1+P_n^* h_1)(h_1+h_2)}}. \tag{22}$$

In $\mathcal{R}_2$, from (7) we have $r_{1n} = \log_2 \left(\frac{(h_1+h_2)(1+h_1 P_n^*)}{h_2 2^{-C_{12}} + h_1 2^{r_{2n}}} \right)$, which can be substituted into (22) and it follows that

$$\frac{dr_{2n}}{dr_{1n}} = -1 - \frac{h_2}{h_1 2^{(r_{2n} + C_{12})}} < -1, \tag{23}$$

which is only determined by r_{2n} and independent of P_n^*.

3) If the point (r_{1n}, r_{2n}) on the curve $\mathcal{G}$ is in the region $\mathcal{R}_3 = \{(r_{1n}, r_{2n}) \in \mathcal{G} \mid 0 < r_{1n} < C_{12}, r_{2n} > C_{21}\}$, it can be proved [10] that

$$\frac{dr_{2n}}{dr_{1n}} = -1 + \frac{h_1}{h_1 + h_2 2^{(r_{1n} + C_{21})}} > -1, \tag{24}$$

which is only determined by r_{1n} and independent of P_n^*. In $\mathcal{R}_3$, we have $\frac{dr_{2n}}{dr_{1n}} > -1 + \frac{h_1}{h_1 + h_2 2^{(C_{12}+C_{21})}}$.

4) If the point (r_{1n}, r_{2n}) on the curve $\mathcal{G}$ is in the region $\mathcal{R}_4 = \{(r_{1n}, r_{2n}) \in \mathcal{G} \mid r_{1n} > C_{12}, r_{2n} > C_{21}\}$, it can be proved [10] that

$$\frac{dr_{2n}}{dr_{1n}} = -\frac{1}{1 + \frac{2^{(-r_1 + C_{12})}\left(h_1^2 - h_2^2\right)}{h_2\left(h_1 2^{(C_{12}+C_{21})} + h_2\right)}} > -1, \tag{25}$$

which is only determined by r_{1n} and independent of P_n^*. In $\mathcal{R}_4$, we have $\frac{dr_{2n}}{dr_{1n}} < -\frac{1}{1 + \frac{h_1^2 - h_2^2}{h_2\left(h_1 2^{(C_{12}+C_{21})} + h_2\right)}}$.

Remark 1 *For a given P_n^*, at most three out of the four regions defined above can be non-empty. For the point (r_{1n}, r_{2n}) in any of the four regions, the derivative $\frac{dr_{2n}}{dr_{1n}}$ exists and there is an unique tangent line at this point. For the point (r_{1n}, r_{2n}) between two adjacent regions, i.e., $r_{1n} = C_{12}$ or $r_{2n} = C_{21}$, the derivative $\frac{dr_{2n}}{dr_{1n}}$ does not exist and the tangent line at this point is not unique.*

By considering the KKT conditions of problem (P4), it can be shown [10] that its optimal solution (r_{1n}^*, r_{2n}^*) should satisfy: 1) $g(r_{1n}^*, r_{2n}^*) = P_n^*$; 2) if the optimal point is in any of the four regions, the slope of the tangent line for the curve $\mathcal{G}$ at this point equals $-\frac{\mu_1}{\mu_2}$, i.e., $\frac{dr_{2n}}{dr_{1n}} = -\frac{\mu_1}{\mu_2}$; if the optimal point is between two adjacent regions, i.e., $r_{1n}^* = C_{12}$ or $r_{2n}^* = C_{21}$, one of the tangent lines for the curve $\mathcal{G}$ at this point has a slope equals $-\frac{\mu_1}{\mu_2}$.

Based on the above observations, we can obtain the optimal solution of problem (P4) for $n = 1, \cdots, N$ as follows, and then by using (8)-(11), we complete the whole transmission scheme.

1) If $-\frac{\mu_1}{\mu_2} < -1$, let the derivative (23) equals $-\frac{\mu_1}{\mu_2}$, we have $r_{2n} = \min\left(\left(\log_2\left(\frac{\mathrm{h}_2+\mu_2}{\mathrm{h}_1(\mu_1-\mu_2)}\right) - \mathrm{C}_{12}\right)^+, \mathrm{C}_{21}\right) = \mathrm{R}_2$. a) if $0 \le P_n^* \le g\left(C_{12}, 0\right)$, the optimal rate allocation is given as $r_{2n}^* = 0$ and r_{1n}^* satisfying $g(r_{1n}^*, 0) = P_n^*$; b) if $g\left(C_{12}, 0\right) < P_n^* \le g\left(C_{12}, R_2\right)$, the optimal rate allocation is $r_{1n}^* = C_{12}$ and r_{2n}^* satisfying $g(C_{12}, r_{2n}^*) = P_n^*$, which is the point between $\mathcal{R}_1$ and $\mathcal{R}_2$; c) if $P_n^* > g\left(C_{12}, R_2\right)$, the optimal rate allocation is given as $r_{2n}^* = R_2$ and r_{1n}^* satisfying $g(r_{1n}^*, R_2)$, which is in $\mathcal{R}_2$. It can be seen that R_2 is the maximum possible transmission rate for transmitter 2, regardless of the sum power value P_n^*, thus we call it as the capping transmission rate at transmitter 2.

2) If $-\frac{\mu_1}{\mu_2} > -1$, the optimal rate allocation is similar to the case $-\frac{\mu_1}{\mu_2} < -1$ discussed above. The difference is that there exists a capping rate at transmitter 1 instead of transmitter 2, which is given by:

i) $R_1 = \left(\log_2\left(\frac{h_1}{h_2}\left(\frac{\mu_2}{\mu_2-\mu_1} - 1\right)\right) - C_{21}\right)^+$, if $-\frac{\mu_1}{\mu_2} > -1 + \frac{h_1}{h_1+h_2 2^{(C_{12}+C_{21})}}$; ii) $R_1 = \log_2\left(\frac{\mu_1(h_2^2-h_1^2)}{(\mu_1-\mu_2)h_2(h_1 2^{(C_{12}+C_{21})}+h_2)}\right) + C_{12}$, if $-\frac{\mu_1}{\mu_2} < -\frac{1}{1+\frac{h_1^2-h_2^2}{h_2\left(h_1 2^{(C_{12}+C_{21})}+h_2\right)}}$; iii) $R_1 = C_{12}$, if $-\frac{1}{1+\frac{h_1^2-h_2^2}{h_2\left(h_1 2^{(C_{12}+C_{21})}+h_2\right)}} \le -\frac{\mu_1}{\mu_2} \le -1 + \frac{h_1}{h_1+h_2 2^{(C_{12}+C_{21})}}$.

3) If $\mu_1 = \mu_2$, it follows that: a) if $P_n^* \le g\left(C_{12}, C_{21}\right)$, the optimal rate allocation is not unique, and any rate pair $\left(r_{1n}^*, r_{2n}^*\right)$ satisfying $r_{1n}^* + r_{2n}^* = \log_2\left(1 + \left(h_1 + h_2\right) P_n^*\right)$, $0 \le r_{1n}^* \le C_{12}$, $0 \le r_{2n}^* \le C_{21}$ is optimal; b) if $P_n^* > g\left(C_{12}, C_{21}\right)$, the optimal rate allocation is given as $r_{2n}^* = C_{21}$ and r_{1n}^* satisfying $g(r_{1n}^*, C_{21}) = P_n^*$, which is the point between $\mathcal{R}_2$ and $\mathcal{R}_4$. In this case, the capping transmission rate at transmitter 2 is equal to C_{21}.

4. NUMERICAL RESULT

In this section, we compare the maximum departure regions obtained by the optimal offline resource allocation scheme discussed in the previous section against an online "on-off" resource allocation scheme. For the online scheme, the two transmitters transmit with a sum power $g\left(r_1, r_2\right) = \bar{P}$ whenever the available power is no smaller than $\bar{P}$; otherwise, the transmission is suspended.

Here we adopt $C_{12} = 2.5$ bits/s/Hz, $C_{21} = 2$ bits/s/Hz, $h_1 = 0.9$, $h_2 = 0.8$, $T = 300$ s. We assume that the energy arrivals follow a Poisson process with average inter-arrival time $l_{ave} = 10$ s. The amounts of harvested energy follow a uniform distribution over $[0, 2E_{ave}]$ J, where $E_{ave} = 100$ J is the average amount of the harvested energy. Therefore, the average charging rate is $\bar{P} = \frac{E_{ave}}{l_{ave}} = 10$ J/s. As can be observed from Fig. 1, with one of the two transmitters sending the same amounts of data for both of the power allocation schemes, the other transmitter can always send more data (by about 150 bits) with the optimal offline algorithm.

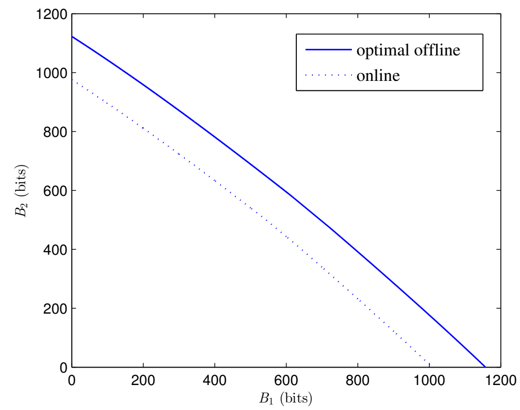

Fig. 1. Maximum Departure Regions obtained by the offline and online algorithms

5. RELATION TO PRIOR WORK

This work adopted the same deterministic EH model as in [1, 4, 5, 6] while considering a novel scenario for MAC with conferencing links and a shared renewable energy source. The work in [6] is closest to ours, where the authors investigated the optimal power allocation for the MAC with independent EH sources and without conferencing between the transmitters. Moreover, we obtained the analytical optimal structure for resource allocation to completely characterize the maximum departure region for the considered channel, while in [6], the authors only presented the analytical optimal structure to quantify part of the corresponding region, and left the rest to numerical solutions.

6. CONCLUSION

In this paper, we studied the optimal resource allocation for the two-user Gaussian MAC with a shared energy harvester and conferencing links under a deterministic EH model. We obtained the structures of the optimal sum power allocation and the optimal rate scheduling over the two transmitters to achieve the boundary of the maximum departure region. We also proved that there exists a capping rate at one of the two transmitters in various scenarios.

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