Energy Efficiency Optimization of Reconfigurable Intelligent Surfaces with Electromagnetic Field Exposure Constraints

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Abstract—This work considers the problem of energy efficiency maximization in a reconfigurable intelligent surface (RIS)-based communication link, subject to not only the conventional maximum power constraints, but also additional constraints on the maximum exposure to electromagnetic radiations of the endusers. The RIS phase shifts, the transmit beamforming, the linear receive filter, and the transmit power are jointly optimized, and two provably convergent and low-complexity algorithms are developed. One algorithm can be applied to the general system setups, but does not guarantee global optimality. The second algorithm is provably optimal in a notable special case. The numerical results show that RIS-based communications can ensure high energy efficiency while fulfilling users' exposure constraints to radio frequency emissions.

I. INTRODUCTION

With fifth generation (5G) networks being rolled out, the attention is shifting towards the next generation of wireless networks. Among the candidate technologies for beyond 5G, the use of reconfigurable intelligent surfaces (RISs) is emerging as a way of ensuring high data rates, high energy efficiency, and a high degree of flexibility to adapt to sudden and heterogeneous service requests [1], [2], [3]. Environmental objects separating the communication endpoints can be coated with RISs, which can be dynamically reconfigured so as to provide channel customization features. In the area of radio resource allocation for RIS-based networks, most contributions focus on maximizing the network rate [4], [5], the energy efficiency [4], [6], or minimizing the power consumption [7].

At the same time, a relevant issue for future wireless networks is the growing concerns for electromagnetic pollution. Although, at present, non-ionizing radio frequency radiations have not been associated to any health condition [8], the continuous exposure to electromagnetic fields (EMF) is a factor that raises concerns among end-users and diminishes their acceptance of emerging transmission technologies and massive network deployments [9]. A few studies have appeared in the literature to investigate resource allocation schemes that minimize the EMF exposure of human users. In [10], a survey on reducing the electromagnetic radiation in wireless systems is provided. In [11], a method for evaluating the specific absorption rate (SAR) of multi-antenna systems is proposed and evaluated. In [12], the EMF exposure in orthogonal frequencydivision multiplexing (OFDM) systems is minimized subject to minimum rate requirements for the users, and the authors of [13] have recently designed transmit policies that dynamically allocate users' electromagnetic radiation exposure over time.

While all these previous works considered the problem of EMF-aware communications in legacy wireless systems,

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an EMF-aware scheme for RIS-based wireless networks has recently been developed in [14]. Therein, the users' electromagnetic exposure is minimized subject to quality of service constraints. Instead, in this work we consider the different and more general problem of maximizing the energy efficiency in an RIS-assisted communication MIMO link, enforcing both maximum power constraints and maximum EMF exposure constraints. The optimization problem is tackled with respect to the RIS phase shifts, the transmit beamforming, the linear receive filter, and the transmit power. The EMF constraints are formulated in terms of maximum acceptable values for the SAR, which measures the rate of electromagnetic energy absorption per unit mass of human body when it is exposed to a radio frequency electromagnetic field [11], [13].

In particular, we devise two provably convergent optimization methods for EMF-aware RIS-assisted communications. The first algorithm leverages alternating maximization and has a complexity that is linear in the number of RIS elements and polynomial in the number of transmit and receive antennas. The second algorithm achieves the global optimal solution without requiring any iterations, in the notable special case of isotropic EMF exposure constraints, enjoying a complexity that is linear in the number of RIS elements and in the number of transmit and receive antennas. The numerical results show that employing RISs can ensure high energy efficiency while fulfilling electromagnetic exposure constraints.

II. SYSTEM MODEL

Consider a single-user system in which a transmitter with N_T antennas and a receiver with N_R antennas communicate through an RIS. The direct link between the transmitter and receiver is assumed to be weak enough to be ignored. Denote by δ the end-to-end path loss, H and G the fading channels from the transmitter to the RIS and from the RIS to the receiver, respectively, p the transmit power, q and w the unitnorm transmit beamformer and receive combiner. The RIS has N elementary passive scatterers, which can independently reflect the radio wave impinging upon them according to a unit amplitude reflection coefficient $e^{j\phi_n}$, $n=1,\ldots,N$ and j denoting the imaginary unit. We assume that a reliable channel estimation phase has been performed, and that the RIS phase configuration can be set by sending a configuration signal to an RIS controller with minimal signal processing, transmission/reception, and power storage capabilities [1, Fig. 4], [4]. Under these assumptions, the system bit-per-Joule energy efficiency is expressed as

$$EE = \frac{B \log_2 \left(1 + \frac{p}{\delta \sigma^2} \left| \boldsymbol{w}^H \boldsymbol{G} \boldsymbol{\Phi} \boldsymbol{H} \boldsymbol{q} \right|^2 \right)}{\mu p + P_c}$$
(1)

with μ the inverse of the transmit amplifier efficiency, P_c the static power consumption of the system, B the communication bandwidth, and σ^2 the receive noise power.

A. EMF-Aware Optimization: Near-Field SAR Constraints

Each portable device must comply with specific SAR limits of radiation that are considered safe for the body [13]. The challenge of fulfilling SAR compliance is exacerbated by the use of multiple transmit antennas in portable wireless devices, which increases the exposure for a given total transmit power, due to the combinations of the precoding gains and phases across the antennas [11]. The objective of this paper is to optimize the RIS matrix Φ , the beamforming vector q, the receive filter w, and the transmit power p, for energy efficiency maximization, subject to both power and EMF constraints.

To this end, we formulate the following problem

$$\max_{\boldsymbol{\Phi},\boldsymbol{q},\boldsymbol{w}} \frac{B \log_2 \left(1 + \frac{p}{\delta \sigma^2} \left| \boldsymbol{w}^H \boldsymbol{G} \boldsymbol{\Phi} \boldsymbol{H} \boldsymbol{q} \right|^2\right)}{\mu p + P_c}$$
(2a)

s.t.
$$\phi_n \in [0, 2\pi]$$
, $0 \leqslant p \leqslant P_{max}$ (2b)

$$\sum_{n=1}^{N_T} c_n |q_n| \leqslant P_q , \sum_{n=1}^{N_T} |q_n|^2 \leqslant 1$$

$$\sum_{n=1}^{N_R} d_n |w_n| \leqslant P_w , \sum_{n=1}^{N_R} |w_n|^2 \leqslant 1 ,$$
 (2d)

$$\sum_{n=1}^{N_R} d_n |w_n| \le P_w \ , \ \sum_{n=1}^{N_R} |w_n|^2 \le 1 \ , \tag{2d}$$

wherein P_{max} is the maximum transmit power, P_q and P_w are the maximum EMF constraints at the transmitter and receiver side, respectively, while $\{c_n\}_{n=1}^N$ and $\{d_n\}_{n=1}^N$ are the EMF absorption coefficients, which account for the magnitude of the total electric field absorbed by the human body due to the beamformer applied by the n-th transmit antenna, with $n = 1, \dots, N_T$, and the receive combiner applied by the nth receive antenna, with $n = 1, ..., N_R$. The EMF constraint does not apply to the RIS because of the unit modulus design assumption of the matrix of reflection coefficients.

III. ENERGY EFFICIENCY MAXIMIZATION

The EE maximization problem will be first tackled in its general form given in (2), for which an iterative method will be developed. Next, a special case of Problem (2) will be globally solved in closed-form.

A. Maximization by Alternating Optimization

A suitable approach to tackle Problem (2) is the alternating optimization of the RIS phase shift matrix Φ , the beamforming vector q, the receive filter w, and the transmit power p. These four subproblems are solved in the next three sections.

1) Optimal Φ : For fixed q, w, p, the problem becomes

$$\max_{\mathbf{A}} |\mathbf{w}^H \mathbf{G} \mathbf{\Phi} \mathbf{H} \mathbf{q}|, \text{ s.t. } \phi_n \in [0, 2\pi],$$
 (3a)

since the denominator does not depend on Φ and the logarithm is an increasing function. Problem (3) is solved by setting $\phi_n = -\angle g_n^* h_n$, where $(\cdot)^*$ is the complex conjugate, g_n and h_n are the *n*-th component of $\mathbf{G}^H \mathbf{w}$ and $\mathbf{H} \mathbf{q}$, respectively.

Algorithm 1 Alternating maximization

Initialize w and q to feasible values. until Convergence Set p as the solution of (7);

2) Optimal q: For fixed Φ , w, p, the optimization becomes

$$\max_{\boldsymbol{q}} |\boldsymbol{v}^{H}\boldsymbol{q}|, \text{ s.t.} \sum_{n=1}^{N_{T}} c_{n} |q_{n}| \leq P_{q}, \sum_{n=1}^{N_{T}} |q_{n}|^{2} \leq 1, (4)$$

wherein ${m v}^H = {m w}^H {m G} {m \Phi} {m H},$ and P_q is the maximum allowed EMF exposure due to the transmit antennas. Since the constraints involve only the moduli of the components of q, it is optimal to set the phases of q_n so as to align the phases of the entries v_n^* in v^H . Plugging $\angle q_n = \angle v_n$ into (4) yields

$$\max_{\{x_n \ge 0\}_n} \sum_{n=1}^{N_T} |v_n| x_n , \text{s.t.} \sum_{n=1}^{N_T} c_n x_n \le P_q , \sum_{n=1}^{N_T} x_n^2 \le 1$$
 (5)

with $x_n = |q_n|$ for n = 1, ..., N. Problem (5) is convex and thus can be globally solved with polynomial complexity.

3) Optimal w: Defining $u = G\Phi Hq$ and denoting by P_w the maximum allowed EMF exposure due to the receive antennas, the same line of reasoning used to optimize q leads us to setting $\angle w_n = \angle u_n$, which yields the problem

$$\max_{\{y_n \ge 0\}_n} \sum_{n=1}^{N_R} |u_n| y_n \text{ , s.t. } \sum_{n=1}^{N_R} d_n y_n \leqslant P_w \text{ , } \sum_{n=1}^{N_R} y_n^2 \leqslant 1 \quad (6)$$

with $y_n = |w_n|$ for n = 1, ..., N. Problem (6) is convex and thus can be globally solved with polynomial complexity.

4) Optimal p: The optimal p is found as

$$\max_{p} \frac{\log_2(1+pc)}{\mu p + P_c} , \text{s.t. } 0 \le p \le P_{max}$$
 (7)

with $c = |\mathbf{w}^H \mathbf{G} \mathbf{\Phi} \mathbf{H} \mathbf{q}|^2 / \delta \sigma^2$. Problem (7) can be seen to be a pseudo-concave maximization, and thus its solution is simply found from the stationarity condition [15].

Finally, the overall optimization algorithm can be stated as in Algorithm 1. Let us observe that, the optimization of p needs to be performed only once, after convergence has been reached for q, w, Φ , since the optimization of q, w, Φ does not depend on the optimal p. As for the convergence of Algorithm 1, the following result holds.

Proposition 1: Algorithm 1 monotonically improves the value of the energy efficiency and converges.

Proof: Each step of Algorithm 1 globally optimizes one of the problem variables, thus leading to an increase of the objective (2b). Therefore, the energy efficiency monotonically increases after each step of Algorithm 1. Since the energy efficiency is an upper-bounded function, Algorithm 1 must converge in the value of the objective.

B. A special case of Problem (2)

Aiming at providing a deeper insight into the structure of the solution of Problem (2), let us consider the notable special case in which $c_n = c$ for $n = 1, ..., N_T$ and $d_n = d$ for n = $1, \ldots, N_R$. This case study is of practical relevance because it is likely that, for typical co-located multi-antenna devices, the human body has the same SAR for every antenna of the array. Next, we also assume that $P_q/c \le 1$ and $P_w/d \le 1$ hold, which corresponds to enforcing particularly demanding EMF constraints. Under these assumptions, the EMF constraints become $\sum_{n=1}^{N_T} |q_n| \leqslant P_q/c$ and $\sum_{n=1}^{N_T} |w_n| \leqslant P_w/d$. Moreover, they imply the unit-norm constraints, because it holds that

$$\sum_{n=1}^{N_T} |q_n|^2 \leqslant \sum_{n=1}^{N_T} |q_n| \leqslant P_q/c \leqslant 1 , \qquad (8)$$

$$\sum_{n=1}^{N_R} |w_n|^2 \leqslant \sum_{n=1}^{N_R} |w_n| \leqslant P_w/d \leqslant 1 , \qquad (9)$$

$$\sum_{n=1}^{N_R} |w_n|^2 \leqslant \sum_{n=1}^{N_R} |w_n| \leqslant P_w/d \leqslant 1 , \qquad (9)$$

At this point, let us revisit the results in Secs. III-A2, III-A3. 1) Optimization of q: Defining $v^H = w^H G \Phi H$ and noting that the optimal phases of the entries of q are $\angle q_n = \angle v_n$, the problem reduces to

$$\max_{\{x_n \geqslant 0\}_n} \sum_{n=1}^{N_T} |v_n| x_n \text{ , s.t. } \sum_{n=1}^{N_T} x_n \leqslant P_q/c \text{ , }$$
 (10a)

with $x_n = |q_n|$ for $n = 1, ..., N_T$. The following result holds. Proposition 2: Denote by $n_q \in \{1, 2, ..., N_T\}$ the index such that $|v_{n_n}| \ge |v_n|$, for $n = 1, \ldots, N_T$. Then, the optimal solution of Problem (10) is given by

$$\begin{cases} x_n = \frac{P_q}{c}, \text{ for } n = n_q \\ x_n = 0, \text{ for } n \neq n_q \end{cases}$$
 (11)

Proof: Since $|v_{n_q}| \ge |v_n|$ for $n = 1, ..., N_T$, there exist non-negative values $\epsilon_1, \ldots \epsilon_{N_T}$ such that $|v_n| = |v_{n_q}| - \epsilon_n$, for $n = 1, ..., N_T$. Then, it holds that

$$\sum_{n=1}^{N_T} |v_n| x_n = |v_{n_q}| x_{n_q} + \sum_{n \neq n_q}^{N_T} (|v_{n_q}| - \epsilon_n) x_n$$

$$= |v_{n_q}| \sum_{n=1}^{N_T} x_n - \sum_{n \neq n_q}^{N_T} \epsilon_n x_n \leqslant |v_{n_q}| P_q / c , \quad (12)$$

where the last inequality follows because $\sum_{n=1}^{N_T} x_n \leqslant P_q/c$ and $\sum_{n \neq \bar{n}}^{N_T} \epsilon_n x_n \geqslant 0$. Finally, the proof follows because the solution in (11) achieves the upper-bound in (12).

2) Optimization of w: Defining $u^H = G\Phi Hq$ and noting that the optimal phases of the entries of w need to fulfill the identity $\angle w_n = \angle u_n$, the problem to be solved reduces to

$$\max_{\{y_n \geqslant 0\}_n} \sum_{n=1}^{N_T} |u_n| y_n \text{ , s.t.} \sum_{n=1}^{N_T} y_n \leqslant P_w/d , \qquad \text{(13a)}$$

with $y_n = |w_n|$ for $n = 1, ..., N_T$. The following result holds. Proposition 3: Denote by $n_w \in \{1, 2, \dots, N_T\}$ the index such that $|u_{n_n}| \ge |u_n|$, for $n = 1, \ldots, N_T$. Then, the optimal solution of Problem (13) is given by

$$\begin{cases} y_n = \frac{P_w}{d}, \text{ for } n = n_w \\ y_n = 0, \text{ for } n \neq n_w \end{cases}$$
 (14)

The proof follows along the same line of reasoning as for the proof of Proposition 2 and it is hence omitted. Based on Propositions 2 and 3, it is possible to obtain the optimal solution of Problem (2) when q, w, Φ , p are jointly optimized. **Algorithm 2** Global optimization with $P_q/c \le 1$, $P_w/d \le 1$.

$$\begin{array}{l} \text{for } i = 1 \text{ to } N_T \text{ do} \\ \text{ for } j = 1 \text{ to } N_R \text{ do} \\ n_q = i; \ n_w = j; \ \text{Obj}(i,j) = \sum_{n=1}^N |\boldsymbol{g}_{n_w}(n)\boldsymbol{h}_{n_q}(n)|; \\ \text{ end for} \\ \text{ end for} \\ (n_q^o, n_w^o) = \operatorname{argmax Obj}(i,j); \\ \boldsymbol{q} = \frac{P_q}{c}[\underbrace{0, \dots, 0}_{n_q^o-1}, 1, 0, \dots, 0]; \ \boldsymbol{w} = \frac{P_w}{d}[\underbrace{0, \dots, 0}_{n_w^o-1}, 1, 0, \dots, 0]; \\ \phi_n = -\angle g_{n_w^o}(n)h_{n_q^o}(n); \ \text{Set } p \text{ as the solution of } (7); \end{array}$$

By direct inspection of Proposition 2 and Proposition 3, in fact, we evince that the optimal q and w have only one non-zero component, and so they can be written as

$$\boldsymbol{q} = \frac{P_q}{c} e^{j\phi_q(\boldsymbol{\Phi}, \boldsymbol{w})} [\underbrace{0, \dots, 0}_{n_q - 1}, 1, 0, \dots, 0]$$
 (15)

$$\boldsymbol{w} = \frac{P_w}{d} e^{j\phi_w(\boldsymbol{\Phi}, \boldsymbol{q})} [\underbrace{0, \dots, 0}_{n_w - 1}, 1, 0, \dots, 0], \qquad (16)$$

where we have highlighted the fact that the optimal ϕ_q will depend on Φ and w through the vector v, and that the optimal ϕ_w will depend on Φ and q, through the vector u. In practice, (15) and (16) imply that, under the assumption of isotropic EMF constraints, the optimal solutions for the transmit beamforming and the receive decoding vectors consist of activating a single antenna at the transmitter and a single antenna at the receiver, which need to be appropriately chosen. Exploiting (15) and (16) we obtain

$$|\boldsymbol{w}^{H}\boldsymbol{G}\boldsymbol{\Phi}\boldsymbol{H}\boldsymbol{q}| = \left| \frac{P_{q}}{c} \frac{P_{w}}{d} e^{j\phi_{q}(\boldsymbol{\Phi},\boldsymbol{w})} e^{-j\phi_{w}(\boldsymbol{\Phi},\boldsymbol{q})} \boldsymbol{g}_{n_{w}}^{T} \boldsymbol{\Phi} \boldsymbol{h}_{n_{q}} \right| = \frac{P_{q}}{c} \frac{P_{w}}{d} \left| \boldsymbol{g}_{n_{w}}^{T} \boldsymbol{\Phi} \boldsymbol{h}_{n_{q}} \right| \leq \frac{P_{q}}{c} \frac{P_{w}}{d} \sum_{n=1}^{N} \left| \boldsymbol{g}_{n_{w}}(n) \boldsymbol{h}_{n_{q}}(n) \right|, \quad (17)$$

wherein $\boldsymbol{g}_{n_w}^T$ is the n_w -th row of \boldsymbol{G} , \boldsymbol{h}_{n_g} is the n_q -th column of H, and the last inequality is obtained with equality upon optimizing Φ , i.e., by choosing $\phi_n = -\angle g_{n_w}(n)h_{n_q}(n)$ for n = 1, ..., N, with $g_{n_w}(n)$ and $h_{n_q}(n)$ being the n-th components of \boldsymbol{g}_{n_w} and \boldsymbol{h}_{n_q} .

Thus, the phases $\phi_q(\mathbf{\Phi}, \mathbf{w})$ and $\phi_w(\mathbf{\Phi}, \mathbf{q})$ do not affect the value of the objective function, regardless of the values of q, w, Φ . Therefore, in order to determine the optimal Φ, q , and w, it remains to optimize the indexes n_w and n_q . This is difficult to be performed in closed-form, but it can be carried out through an exhaustive search over all possible $N_T N_R$ choices of the pair (n_w, n_q) . Finally, the optimal transmit power can be determined as in Section III-A4 once the optimal Φ , q, and w have been computed.

Thus, the overall globally optimal resource allocation procedure can be given as in Algorithm 2. It computes (17) for each choice (n_w, n_q) , selects the choice (n_w^o, n_q^o) that yields the largest value of (17), and then allocates the system resources accordingly.

C. Complexity analysis

Let us compare the complexity of Algorithms 1 and 2.

As for Algorithm 1, each of the subproblems can be easily solved, since Φ can be optimized with linear complexity by computing N times the quantity $\phi_n = -\angle g_n^* h_n$, while q and w have a polynomial complexity in N_T and N_R , respectively, since Problems (5) and (6) are concave¹. As for the complexity related to computing p, it is negligible since (7) is a scalar problem which needs to be solved just once. Finally, the overall complexity of Algorithm 1 scales linearly with the number I of iterations required to reach convergence.

Algorithm 2 has a lower complexity, since it is not iterative (i.e. I=1), and the complexity is linear in N, N_R , and N_T . Indeed, the variable $\mathrm{Obj}(i,j)$ needs to be computed N_TN_R times, and each computation requires N complex multiplications. Finally, the same negligible complexity as for Algorithm 1 is required to optimize p.

IV. NUMERICAL RESULTS

In our numerical analysis, we set $B=5\,\mathrm{MHz}$, $\delta=110\,\mathrm{dB}$, $N_0=-174\,\mathrm{dBm/Hz}$, $N_T=N_R=4$, $P_c=30\,\mathrm{W}$, $P_{max}=20\,\mathrm{W}$. As for the fading channels, a Rician model is considered, wherein $h_n\sim\mathcal{CN}(v_h,1)$ and $g_n\sim\mathcal{CN}(v_g,1)$, with v_h and v_g such that the power of the line-of-sight path is four times larger than the power of all the other paths. All results are averaged over 10^3 independent channel realizations. Moreover, $c_n=c=1/N_T$ and $d_n=d=1/N_R$. For simplicity, thus, we consider the isotropic EMF setup.

Figures 1 and 2 show the system energy efficiency and the EMF exposure $c \sum_{n=1}^{N} |q_n|$, respectively, as a function of P_q/c for N=100, and as a function of N for $P_q/c=0.85$. The following schemes are considered and evaluated:

- (a) The EMF-aware alternating optimization of q, w, Φ , and p by Algorithm 1.
- (b) The EMF-aware globally optimal optimization of q, w, Φ , and p by Algorithm 2. Here, the curve is shown only in the range $P_q/c \le 1$, since beyond this value the assumptions in Section III-B1 do not hold.
- (c) The EMF-aware alternating optimization of q and w by Algorithm 1. Here, the RIS matrix Φ is not optimized and each phase shift is randomly set in $[0, 2\pi]$.
- (d) The EMF-aware globally optimal optimization of q, w, and p, by Algorithm 2. Also in this case, each RIS phase shift is randomly set in $[0,2\pi]$. Moreover, this curve is shown in the range $P_q/c \leqslant 1$, since beyond this value the assumptions in Section III-B1 do not hold.
- (e) The EMF-unaware optimization of q, w, Φ , and p by the alternating optimization method from [4].
- (f) The EMF-unaware optimization of q, w, and p, by the alternating optimization method from [4]. In this case, each RIS phase shift is randomly set in $[0, 2\pi]$.

From Figs. 1 and 2, we observe that enforcing an EMF constraint on the SAR of the human body reduces the energy efficiency level, since it restricts the feasible set of the problem. The use of RISs offers, however, the opportunity of

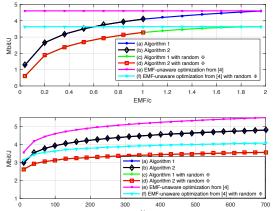


Fig. 1. Average energy efficiency of th six considered schemes as a function of (top) P_q/c for N=100 and (bottom) N for $P_q/c=0.85$.

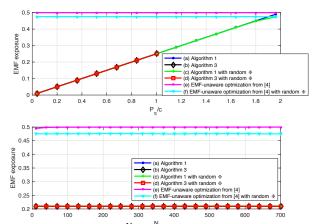


Fig. 2. EMF constraint $c\sum_{n=1}^N|q_n^{\rm N}|$ of the six considered schemes as a function of (top) P_q/c for N=100 and (bottom) N for $P_q/c=0.85$.

achieving the desired energy efficiency while ensuring SARcompliant communications. Figure 1 shows, in particular, that, by increasing N, we can attain the same energy efficiency as the benchmark systems in the absence of EMF constraints. EMF-aware transmission schemes lead, on the other hand, to large values of the EMF exposure $c\sum_{n=1}^{N}|q_n|$ (i.e., the EMF exposure), which may not fulfill the desired SAR values specified by national and international regulations. It is particularly interesting to note that increasing N has little or no impact on the EMF exposure $c\sum_{n=1}^{N}|q_n|$ imposed to the transmit and receive filters. Also, Algorithm 1 offers similar performance as the globally optimal solution obtained with Algorithm 2, although at a higher complexity. Moreover, as expected, the SAR-constrained energy efficiency tends, for large values of P_q/c , to the benchmark energy efficiency in the absence of EMF constraints. This is because increasing P_q/c makes the EMF constraint become less relevant.

V. CONCLUSIONS

Low-complexity optimization algorithms have been proposed for energy efficiency maximization subject to EMF constraints. The analysis has shown that the use of a RIS can keep under control the end-users' EMF exposure while ensuring the desired energy efficiency level. Notably, this is obtained by using nearly-passive RISs that do not increase the amount of electromagnetic radiation over the air.

 $^{^1{\}rm The~order}~\alpha$ of the polynomial is not available in closed-form, but a known worst-case bound is $\alpha=4$

²We focus on the exposure due to the transmit antennas. Similar results hold for the EMF exposure due to the receive antennas.

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