5G Networks Supported by UAVs, RESs, and RISs

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Abstract— This paper presents the examination of the 5G cellular network aware of Renewable Energy Sources (RESs) and supported by Reconfigurable Intelligent Surfaces (RISs) and Unmanned Aerial Vehicles working as mobile access nodes. The investigations have been focused on the energy side of the Radio Access Network (RAN) placed within the area of the city of Poznan (Poland). The gain related to enabling RES generators, i.e., photovoltaic (PV) panels, for base stations (BSs) was presented in the form of two factors – the average number of UAV replacements (ANUR) with a fully charged one to ensure continuous access to mobile services for currently served user equipment (UE) terminals, and the average reduction in energy consumption (AREC) within the whole network.¹

Index Terms—5G, cellular networks, energy consumption, Reconfigurable Intelligent Surfaces, Renewable Energy Sources, Unmanned Aerial Vehicles

I. INTRODUCTION

Nowadays, telecommunication systems are powered mainly by fossil fuels. Those systems contribute about 25% to the total value of carbon dioxide (CO_2) emissions caused by the Information and Communication Technology (ICT) segment, which shows an increasing trend in energy demand from one year to another [1]. Furthermore, currently, the ICT sector is responsible for a huge part of global Green House Gas (GHG) emissions, which are maybe underestimated and could actually be even as high as 2.1 to 3.9% [2]. Hence, to deal with this issue the necessity of finding alternative sources of power that will both meet the energy demand of wireless systems (4G, 5G, and beyond) and reduce the amount of produced CO_2 emissions to the atmosphere might be required. Therefore, the engagement of Renewable Energy Sources (RESs), e.g., photovoltaic (PV) panels seems to be an appropriate solution [3]. However, it is still hard to be unequivocally stated whether the use of solar cells is much more environment-friendly (in terms of entailing emissions) or not, especially taking into Adrian Kliks

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account the processes of their production and utilization. On the contrary, the way of harvesting electrical energy from solar radiation seems to be non-polluting itself and the amount of potentially generated resources can be considered to some extent as endless (excluding the need to replace/renovate PV panels after some time period) in a long-term context [4].

Within the concept of cellular systems of the 5th generation, mobile services are divided into 4 main groups: Enhanced Mobile Broadband (eMBB), Critical Communications (CC) and Ultra Reliable Low Latency Communications (URLLC), Massive Internet of Things (mIoT), and flexible network operations, where first 3 of them, in short, assume the provision of high throughput, low latency, and a big number of connected devices at the same time, respectively [5]. From the perspective of delivering the first case, there may appear a limitation related to a finite number of physical resource blocks (PRBs) per network cell. This issue might be noticed especially in urban areas, where the population is quite dense. Thus, to guarantee sufficient capacity and bit rate in a given area, the idea of deploying base stations covering regions with socalled small cells has been developed. This idea of wireless system implementation is based on the provision of RAN with low-power access nodes distributed very close to each other. However, while bringing this small cell concept to life due to obstacles such as unfavorable city architecture or money deficits for building new stationary base stations, there is a risk of signal gap appearance. One of the approaches to handle this issue, which is more and more often taken under consideration in scientific works is the employment of additional supportive equipment, e.g., Unmanned Aerial Vehicles (UAVs) as mobile base stations (MBSs). This, in turn, gives mobile network operators (MNOs) the ability to dynamically adjust the actual locations of access nodes to cover radio signal gaps and/or support existing telecommunication infrastructure in serving areas (urban or remote), where the number of simultaneously connected user terminals can also fluctuate and even exceed primary assumed capacity (e.g., due to public events) [6], [7].

Besides, the use of so-called Reconfigurable Intelligent Surfaces (RISs) to control the radio signal coverage of wireless systems has got great attention in the current literature. The RIS is a device in the form of a surface consisting of a large number of passive (or sometimes active) reflecting elements, which are able to independently cause a desired change in phase and/or amplitude of the incident radio signal. As a consequence of assuring flexible reconfiguration of signal

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propagation (after enabling RISs), MNOs would be able to accomplish better performance of their networks by reducing interferences and dropouts and raising the reliability, capacity, and throughput of radio links [8], [9].

Thus, in this paper, we evaluate the true performance of the UAVs working as base stations, which are equipped with both RISs (for potential future use) and RESs (for extension of the operating time). The goal of this analysis is to find the most appropriate deployment and setup of the drone base stations over a certain area while considering the transmission power, the energy consumed by UAVs for their operation, and the energy production by the RESs. We evaluate the trade-off between the additional mass needed to carry RES and RIS elements and the gains related to energy generated by RESs. Finally, we carry out simulations based on real atmospheric data to verify the true performance of such a solution.

II. SCENARIO

The scenario considered in the work takes into account the 5G cellular network placed within the old market of the city of Poznan in Poland (data given in [10]), the base stations of which are UAVs located based on the real data of one of the Polish mobile operator (given in [11]) and hovering 50 m above the ground. For this study, there was assumed that the placements of the drones do not change over time. Around the city, there are 100 outdoor users distributed randomly with fixed bit rate requirements equal to 100 Mbps per each. In Fig. 1 the map presenting the above-described scenario of the wireless system has been attached.



Fig. 1. Map of the examined area within the city of Poznan.

A. Network Design

The examined network has been designed according to the planner tool described in [12] named Green Radio Access Network Design (GRAND). This tool projects and optimizes radio access networks toward power consumption and/or human exposure by enabling the optimal number of cells of base stations with predefined locations and adjusting their transmission parameters based on the instantaneous throughput requirements of user terminals connected to the wireless system. As the input data, the GRAND tool receives the lists of available base stations and active users with their specific transmission data, and the shape files describing the considered environment (in 3D) including buildings and coverage area. The location of each user is chosen randomly within the provided simulator for every single run. In addition, in the very beginning, all transceivers of access nodes broadcast the radio signal with maximum power. After distributing users within the zone of study, the planner software selects which one of the network cells shall be enabled and with what power they shall transfer the data to reach as many active users as possible. Within this step, the GRAND tool assesses potential radio links between the system and each UE based on the bit rate requested by it as well as the maximum allowable path loss for a particular association for different transmit power configurations. Next, when the graph of accessible BS-UE relations is prepared, a mixed integer programming (MIP) solver is engaged to search for the optimal result. In order to obtain this result an objective function is formulated based on the envisioned optimization of human exposure, power consumption, or both. Afterward, all the users start exchanging data with appropriate access nodes in a continuous manner causing a fixed traffic load throughout the whole time of a single simulation run. Simultaneously, energy balance calculations for all base stations are done, which are further translated to an average number of needed battery recharging per UAV with and without RESs.

B. Equipment

The implementation of PV panels within the GRAND tool software has been inspired by the specifications of the real device, which can be found in [13]. However, it has been assumed that used PV panels are mounted on the top of the UAV's cover in the form of thin-film solar cells. Thus, because of the insignificant impact on the total power consumption of a single mobile base station, the weight of PV panels was omitted during all calculations devoted to energy characteristics within a simulation run. In addition, those calculations have been performed for 4 various days (each starting a different season of the year) to indicate how the harvesting of energy by PV panels depends on the time of the year in Poland.

Similarly, as for solar panels, the battery systems for UAV BSs have been also designed based on the real implementation described in [14]. The objectives of using batteries for drones are to power them in order to fulfill the energy demand as well as to store the resources produced by RES generators connected to them. The lack of electrical energy delivered by the battery cells entails a need to replace the UAV with another one but fully charged. Nevertheless, it has been posited that batteries can be completely drained, and 5% of the total energy kept in a single one is always used for flights before and after the service.

The transceivers of UAV access nodes work in accordance with the Multiple-Input-Multiple-Output (MIMO) technology using 64 active antenna elements (AAE) transmitting radio signals in the 3500 MHz frequency band. The methods of channel estimation and signal processing adopted in the software are consistent with the minimum mean-squared error (MMSE) schema. Furthermore, each of those mobile base stations has also one device of RIS type with 16 identical passive reflecting elements performing phase shifting with a 6-bit resolution of the impinging radio signal. For the following study, the impact of RISs implementation within the examined area on radio signal propagation has been neglected contrary to its influence on the energy balance of the wireless system. However, their effect on the performance of the network will be taken into consideration in future work.

C. Energy Models

All energy models used to provide the mathematical calculations within the GRAND tool (related to energy production and consumption – prosumption) have been directly taken from or inspired by scientific literature or real implementations.

1) UAV Device: Due to the system design concept, it was assumed that UAV access nodes do not change their positions during the simulation. Thus, within the evaluation of energy consumption related to the movement, there is only a need to assess the utilization caused by UAV hovering (P_{UAV}). Thus, according to [15], we present the following formula:

$$P_{\text{UAV}}\left(t\right) = \sqrt{\frac{\left(\left(m_{\text{UAV}} + m_{\text{PKG}}\right) \cdot g\left(t, h_{\text{UAV}}\right)\right)^{3}}{2 \cdot \pi \cdot r_{\text{p}}^{2} \cdot l_{\text{p}} \cdot \rho\left(t, h_{\text{UAV}}\right)}}, \quad (1)$$

where t is the current time step and $m_{\rm UAV}$ and $m_{\rm PKG}$ are the masses of the UAV and the package that is lifted by it. In our case $m_{\rm PKG} = N_{\rm MIMO} \cdot m_{\rm MIMO} + N_{\rm RIS} \cdot m_{\rm RIS} + N_{\rm PV} \cdot m_{\rm PV} + m_{\rm AUX}$, where $m_{\rm MIMO}$, $m_{\rm RIS}$, and $m_{\rm PV}$ are the masses of a single transceiver, RIS array, and PV panel, and $N_{\rm MIMO}$, $N_{\rm RIS}$, and $N_{\rm PV}$ are their numbers, respectively. The parameter of $m_{\rm AUX}$ is the mass of the auxiliary hardware/package carried by the UAV. Next, $l_{\rm p}$ and $r_{\rm p}$ are the number of UAV propellers and the radius of a single one, adequately. Finally, g and ρ are the gravitational acceleration and air density at the altitude $h_{\rm UAV}$ and time moment t.

2) *RIS Array:* Each UAV base station is equipped with a single RIS array in order to improve the efficiency of radio signal broadcasting by its reflecting. Although within this study the use of RISs is omitted for the propagation (human exposure) side of the network design, as a form of preparation for further investigations, the examination of the impact of employing RISs on the energy demand of the wireless system (P_{RIS}) has been taken into considerations as well. Hence, referring to [8], we propose the model attached below:

$$P_{\text{RIS}}(t) = N_{\text{RIS}} \cdot N_{\text{RE}} \cdot P_{\text{PSH}}(b_{\text{PSH}}), \qquad (2)$$

where N_{RIS} , N_{RE} are the numbers of used arrays and identical reflecting elements per single RIS, which effectively perform phase shifting on the impinging signal. Next, P_{PSH} is the power consumption of each phase shifter, which is dependent on the bit resolution b_{PSH} of the used type.

3) MIMO Transceiver: The model used to estimate the power consumed by radio hardware has been formulated in accordance with the work contained in [16]. The mathematical formula that evaluates the total power consumption (P_{MIMO}) by a single transceiver in the current time step t is as below:

$$P_{\text{MIMO}}(t) = P_{\text{CP}}(t) + P_{\text{PA}}(t), \qquad (3)$$

where $P_{\text{PA}}(t) = \frac{P_{\text{TX}}(t)}{\mu_{\text{PA}}}$ is the power consumed by the power amplifier. The parameters of P_{TX} and μ_{PA} are the transmit power and efficiency of the amplifier, respectively. Next, the P_{CP} is the power spent by circuit components of the transceiver, which is expressed as follows:

$$P_{\rm CP}(t) = P_{\rm FIX} + P_{\rm TC}(t) + P_{\rm CE}(t) + P_{\rm C/D}(t) + P_{\rm BH}(t) + P_{\rm SP}(t), \qquad (4)$$

where P_{FIX} is the fixed power consumed by a cell node. The parameter of $P_{\text{TC}}(t) = M_{\text{BS}}(t) P_{\text{CC}}$ is the power utilized by the transceiver chains in the time step t, where P_{CC} is the power that is required to run the circuit components (e.g. filters, I/Q mixers, etc.), and $M_{\rm BS}$ is the number of presently active antenna elements of the cell. Next, $P_{CE}(t) =$ $\frac{3B_{\rm w}}{\tau_{\rm c} \eta_{\rm BS}} K_{\rm UE}\left(t\right) \left(M_{\rm BS}\left(t\right) \tau_{\rm p}\left(t\right) + M_{\rm BS}^2\left(t\right)\right) \text{ is the power needed}$ by the channel estimators, which work according to the minimum mean-squared error (MMSE) scheme [16]. The parameters of $B_{\rm w}$ and $\eta_{\rm BS}$ are the channel bandwidth and computational efficiency, respectively. In addition, $\tau_{p}(t) =$ $RF \cdot K_{UE}(t)$ is the number of samples allocated for pilots per coherence block in a specific time step t, where RF is the pilot reuse factor and $K_{\rm UE}$ is the current number of served users. In turn, $\tau_{\rm c} = B_{\rm c} \cdot t_{\rm c}$ is the number of samples per coherence block, where B_c and t_c are the coherence bandwidth and time, respectively. Furthermore, $P_{C/D}(t) = P_{COD} \cdot TR_{DL}(t) + P_{DEC} \cdot$ $TR_{UL}(t)$ is the total power consumed by a transceiver of the UAV BS for encoding (P_{COD}) and decoding (P_{DEC}) the information transferred through uplink, in short UL, (TR_{UL}) and downlink, in short DL, (TR_{DL}) connections in a particular time step t. The power model takes into account also the load-aware part of the consumption referring to the backhaul links – $P_{BH}(t) = P_{BT}(TR_{UL}(t) + TR_{DL}(t))$, where P_{BT} is the backhaul traffic power. Finally, the power required by the network cell for operations related to signal processing (e.g., UL reception and DL transmission, computation of the combining/precoding vectors) compliant with the MMSE

scheme (P_{SP}) is as below:

$$P_{\rm SP}\left(t\right) = \frac{3B_{\rm w}}{\tau_{\rm c} \cdot \eta_{\rm BS}} \left[M_{\rm BS}\left(t\right) K_{\rm UE}\left(t\right) \left(\tau_{\rm u}\left(t\right) + \tau_{\rm d}\left(t\right)\right)$$
(5)

$$+\frac{\left(3M_{\rm BS}(t)^{2}+M_{\rm BS}(t)\right)K_{\rm UE}(t)}{2}+\frac{M_{\rm BS}(t)^{3}}{3}+2M_{\rm BS}(t) +M_{\rm BS}(t)\tau_{\rm p}(t)\left(\tau_{\rm p}(t)-K_{\rm UE}(t)\right)+M_{\rm BS}(t)K_{\rm UE}(t)\right],$$

where $\tau_{d}(t)$ is the number of DL data samples per coherence block in the time step t.

4) *PV Panel:* There is also a need to model the energy harvesting process performed by PV panels mounted on the cover of each UAV access node. The output power of the set of PV arrays (P_{PV}) in a certain time step t is denoted as [17]:

$$P_{\rm PV}(t) = N_{\rm PV} P_{\rm R, PV} f_{\rm PV} \cdot \frac{\overline{G}_{\rm T}(t)}{\overline{G}_{\rm T, STC}} \bigg[1 + \alpha_{\rm P} \Big(T_{\rm c}(t) - T_{\rm c, STC} \Big) \bigg],$$
(6)

where N_{PV} , $P_{\text{R,PV}}$, and f_{PV} are the total number of PV panels allocated per network cell, and the rated power and derating factor of a single one. In addition, the first one is the multiplication of the numbers of PV panels connected in series ($N_{\text{PV,s}}$) and parallel ($N_{\text{PV,p}}$). Next, \overline{G}_{T} and T_{c} are the parameters that denote the solar radiation incident on the PV array and its temperature. Thus, $\overline{G}_{\text{T,STC}}$ and $T_{\text{c,STC}}$ define the values of the same parameters but for standard test conditions (STC). Finally, α_{P} is the temperature coefficient of power dependent on the type of used PV panels. Besides, to assess the temperature of the PV cell (T_{c}), the formula is used [17]:

$$T_{c}(t) = \frac{T_{a}(t, h_{PV})}{1 + (T_{c,NOCT} - T_{a,NOCT}) \left(\frac{\overline{G}_{T}(t)}{\overline{G}_{T,NOCT}}\right) \left(\frac{\alpha_{P}\mu_{mp,STC}}{\tau\alpha}\right)} (7)$$

+
$$\frac{(T_{c,NOCT} - T_{a,NOCT}) \left(\frac{\overline{G}_{T}(t)}{\overline{G}_{T,NOCT}}\right) \left[1 - \frac{\mu_{mp,STC}(1 - \alpha_{P}T_{c,STC})}{\tau\alpha}\right]}{1 + (T_{c,NOCT} - T_{a,NOCT}) \left(\frac{\overline{G}_{T}(t)}{\overline{G}_{T,NOCT}}\right) \left(\frac{\alpha_{P}\mu_{mp,STC}}{\tau\alpha}\right)},$$

where $T_{c,NOCT}$, $T_{a,NOCT}$, and $\overline{G}_{T,NOCT}$ are the nominal operating cell temperature (NOCT) of the PV panel, and the ambient temperature and solar radiation at which the NOCT is defined, respectively. Next, τ , α , and $\mu_{mp,STC}$ are the solar transmittance of any cover over the PV array and its solar absorptance, and the maximum power point efficiency of the PV panel under STC. This efficiency is equal to $\mu_{mp,STC} = \frac{P_{R,PV}}{a_{PV} \cdot \overline{G}_{T,STC}}$, where a_{PV} and b_{PV} are the dimensions of a single PV module. In turn, the parameter of h_{PV} is the ground-relative altitude of the PV panels powering a specific cell.

5) Battery System: In order to shape the energy management within the battery system (E_{BATT}) of each UAV, inspired by [18] we propose a new model specified below:

$$E_{\text{BATT}}(t) = \begin{cases} E_{\text{BATT}}(t') + \Delta E_{\text{BATT},1}(t), & \text{if } \Delta E(t) > 0\\ E_{\text{BATT}}(t') + \Delta E_{\text{BATT},2}(t), & \text{otherwise} \end{cases},$$
(8)

where $E_{\text{BATT}}(t')$ is the energy handled by the battery system in the previous time step t'. Next, $\Delta E_{\text{BATT},1}$ and $\Delta E_{\text{BATT},2}$ are the energy amounts that have to be transferred from/to the battery system in the current time step t. Finally, ΔE is the energy balance, i.e., the difference between required energy and harvested one at the same moment. The parameters of $\Delta E_{\text{BATT},1}$ and $\Delta E_{\text{BATT},2}$ can be expressed by the formulas:

$$\Delta E_{\text{BATT},1}(t) \qquad (9)$$
$$= \max\left(\Delta E(t) \cdot \mu_{\text{BATT}}, E_{\text{BATT},\text{max}} - E_{\text{BATT}}(t')\right),$$

$$\Delta E_{\text{BATT},2}(t) = \max\left(\frac{\Delta E(t)}{\mu_{\text{BATT}}}, -E_{\text{BATT}}(t')\right), \quad (10)$$

where μ_{BATT} and $E_{\text{BATT,max}}$ are the efficiency of the used battery type and maximum energy the battery system is able to collect, respectively. The latter is equal to $E_{\text{BATT,max}} = N_{\text{BATT}}E'_{\text{BATT,max}}$, where $E'_{\text{BATT,max}}$ is the maximum energy of a single battery, and $N_{\text{BATT}} = N_{\text{BATT,s}}N_{\text{BATT,p}}$ is the total number of accumulator units in a battery system. The parameters of $N_{\text{BATT,s}}$ and $N_{\text{BATT,p}}$ are the numbers of batteries linked to each other in serial and parallel order, respectively. To evaluate the current energy balance (ΔE), the formula below was engaged:

$$\Delta E(t) = (11) \left(P_{\text{PV}}(t) - \frac{P_{\text{UAV}}(t) + P_{\text{MIMO}}(t) + P_{\text{RIS}}(t)}{1 - \sigma_{\text{DC}}} \right) \left(t - t' \right),$$

where σ_{DC} is the loss factor related to DC supplying the hardware parts of the UAV device.

6) Atmospheric Parameters: Finally, let us collect all auxiliary formulas used to calculate necessary atmospheric parameters. The air density (ρ) at the altitude h and in the current time step t can be calculated as follows [19]:

$$\rho(t,h) = (12) \\
\frac{p_{\rm d}(t,h)}{R_{\rm d} \cdot \left(T_{\rm a}(t,h) + 273.15\right)} + \frac{p_{\rm v}(t,h)}{R_{\rm v} \cdot \left(T_{\rm a}(t,h) + 273.15\right)},$$

where R_d and R_v are the specific gas constants for dry air and water vapor, respectively. Next, p_d and p_v are the pressures of dry air and water vapor. The latter at the altitude h and in the time step t can be expressed by the formula [19]:

$$p_{\rm v}\left(t,h\right) = 6.1078 \cdot 10^{\frac{7.5 \cdot T_{\rm a}\left(t,h\right)}{T_{\rm a}\left(t,h\right) + 237.3}},\tag{13}$$

The pressure of dry air at the same altitude and moment has been described by $p_{d}(t,h) = p(t,h) - p_{v}(t,h)$, where p is the air pressure evaluated as [19]:

$$p(t,h) = p_0(t) \cdot e^{\frac{-g(h) \cdot M \cdot (h+h_{\rm T}-h_0)}{R \cdot T_{\rm a}(t,h)}},$$
(14)

where p_0 is the air pressure at the reference level h_0 . It was assumed that the reference level is the sea level altitude $(h_0 = 0)$. The parameter of h_T is the absolute altitude of the terrain. Next referring to [20], the gravitational acceleration is described by $g(h) = g_0 \frac{r_e^2}{(r_e+h)^2}$, where g_0 and r_e are the sea level acceleration and mean radius of the Earth, respectively. Finally, the formula to calculate the ambient temperature (T_a) at the altitude h and moment t is shown below [19]:

$$T_{\rm a}(t,h) = T_{\rm a}(t,h_{\rm WS}) - 0.0065(h+h_{\rm T}-h_{\rm WS}),$$
 (15)

where h_{WS} is the absolute altitude, at which the measurements of weather conditions have been done (the altitude of the weather station – WS).

III. SIMULATION SETUP

The source code of the developed software was prepared in Java language. The examination of the system scenario described in Section II has been performed in the form of 10 independent simulation runs each considering 4 days of the previous year starting different seasons - vernal equinox (20th March 2022), summer solstice $(21^{st}$ June 2022), autumn equinox $(23^{rd}$ September 2022), and winter solstice (21st December 2022). The parameters of users (location coordinates and traffic demand) have always been defined at the beginning of each simulation run. The assumed time step was equal to 1 minute $(4 \cdot 24 \cdot 60 = 5,760$ steps per simulation run), with which the weather data was updated, and then the calculations for energy production and consumption (proesumption) were carried out. The simulation setup for network and energy designs is highlighted in Tab. I and II.

 TABLE I

 NETWORK DESIGN CONFIGURATION [10]–[12], [16]

-					
	Parameter Sign		Unit	Value	
	i arameter	Sign	Om	BS	UE
_	Quantity	K	-	8	100
ral	Movement Speed	v	[m/s]	N/A	0
) ve	Placement	-	-	N/A	outdoor
	Technology	-	-	5G	N/A
	Frequency	f	[MHz]	3500	N/A
	Channel Bandwidth	$B_{\rm w}$	[MHz]	120	N/A
	Used Subcarriers	N _{SC,u}	-	320	N/A
	Total Subcarriers	N _{SC,t}	-	512	N/A
9	Sampling Factor	SF	-	1.536	N/A
an	Pilot Reuse Factor	RF	-	1	N/A
m	Coherence Time	t _c	[ms]	50	N/A
	Coherence Bandwidth	$B_{\rm c}$	[MHz]	1	N/A
	TDD Duty Cycle DL	D _{DL}	[%]	75	N/A
	TDD Duty Cycle UL	D _{UL}	[%]	25	N/A
	Spatial Duty Cycle	S	[%]	25	N/A
	Antenna Height	h	[m]	50	1.5
ers	Antenna Elements	M	-	64	1
iei,	Antenna Gain	Ga	[dBi]	24	0
usc	Antenna Feeder Loss	$L_{\rm f}$	[dB]	3	0
[rai	Max. Transmit Power	P _{TX,max}	[dBm]	42	23
	Noise Figure	NF	[dB]	7	N/A
	Path Loss Model	-	-	TR 38.901	N/A
ttion	Interference Margin	IM	[dB]	2	0
	Doppler Margin	DM	[dB]	3	N/A
age	Fade Margin	FM	[dB]	10	N/A
do	Shadow Margin	SM	[dB]	10	N/A
P 1	Implementation Loss	IL	[dB]	3	N/A
1	Soft Handover Gain	Geno	dB	N/A	0

IV. RESULTS

The results of performed simulations have been attached within Tab. III. The first array presents the amount of energy that can be harvested by PV panels of a single UAV during

TABLE II ENERGY PROSUMPTION CONFIGURATION [8], [10], [13], [14], [16], [18]–[20], [22]–[24]

	Parameter	Sign	Unit	Value
vice	Mass of UAV	mUAV	[kg]	2
	Auxiliary Mass	mAUX	kg	0
	Auxiliary Power	PAUX	W	0
Ď	Hovering Altitude	huav	ĺmĺ	50
UAV	Single Propeller Radius	T _p	m	0.5
	Number of Propellers	l _n	_	12
	DC Loss Factor	$\sigma_{\rm DC}$	-	0.075
	Mass of MIMO Transceiver	m _{MIMO}	[kg]	1
	Fixed Power Component	Prix	W	10
vei	Local Oscillator Power	PLO	W	0.2
cei	Circuit Components Power	Pcc	W	0.4
sur	Encoding Power	Pcop	W	0.1
Ξ.	Decoding Power	PDEC	W	0.8
0	Backhaul Traffic Power	PRT	W	0.25
Ξ	Computational Efficiency	nps	[Gflops/W]	75
Σ	Amplifier Efficiency	1/03	[=====================================	0.35
	Number of Transceivers	NMMO	_	1
	Mass of RIS	mpie	[kø]	1
ay	Phase Shifter Power	Preu	W	7.8
Ψu	Phase Shifter Bit Resolution	hpou	[hits]	6
s	Number of Reflecting Elements	Npr	[0113]	16
RI	Number of RISs	Nnic	-	10
	Model	1 KIS	olarland SI PO20	1-1911
	Mass of PV			0
	Nominal Voltage	V pv	[Kg]	12
	Voltage at Max Power	V n,PV		17.9
	Current at Max. Power	V max, PV		11.2
	Pated Power	Prax, PV		20
	Ground relative Altitude	1 R,PV	[**]	50
	Module Dimensions	npv	m	0.576 x 0.357
G		apv x opv	[III]	0.570 X 0.557
an	Solar Radiation at SIC	GT,STC	W/m ²	1000
/ F	Solar Radiation for NOCT	G _{T,NOCT}	W/m ²	800
Ч	Temperature under STC	T _{c,STC}	[°C]	25
	Temperature NOCT	$T_{c,NOCT}$	[°C]	47
	Temperature Coeffi. of Power	$\alpha_{\rm PV}$	[%/°C]	-0.5
	Solar Absorptance	α	-	$0.3\sqrt{10}$
	Solar Transmittance	τ	-	$0.3\sqrt{10}$
	Derating Factor	f_{PV}	-	0.723
	Number in Serial Order	N _{PV,s}	-	1
	Number in Parallel Order	N _{PV,p}	-	5
	Total Number per Net. Cell	$N_{\rm PV}$	-	5
	Model	Volt Accu	mulator LiFePO	4 12.8V 60Ah
	Mass of Battery	m_{BATT}	[kg]	5.2
	Nominal Voltage	V _{n,BATT}	[V]	12.8
	Charging Voltage	V _{c,BATT}	[V]	14.6
	Discharging Voltage	$V_{d,BATT}$	[V]	12.8
E	Charging Current	I _{c,BATT}	[A]	30
ste	Discharging Current	I _{d,BATT}	[A]	60
S	Capacity	CBATT	[Ah]	60
Ţ,	Provided Energy	$E'_{BATT,max}$	[Wh]	768
atte	Max. Depth of Discharge	DoDmax	[%]	100
ä	Primary State of Charge	SoCp	[%]	95
	Battery's Efficiency	μ_{BATT}	-	0.95
	Number of Cycles	N _{BC}	-	2000
	Number in Serial Order	N _{BATT,s}	-	1
	Number in Parallel Order	N _{BATT,p}	-	1
	Total Number per Net. Cell	NBATT	-	1
Other	Reference Altitude	h_0	[m]	0
	Terrain Absolute Altitude	hT	[m]	54.44
	Weather Station Absolute Alti.	h _{WS}	[m]	90
	Mean Radius of the Earth	re	[m]	6371009
	Sea Level Gravitational Accel.	g_0	m/s^2	9.80665
	Air Molar Mass	m _{air}	[kg/mol]	0.0289644
	Universal Gas Constant	Ru	$\left[\frac{\mathbf{N} \cdot \mathbf{m}}{\mathbf{m} \mathbf{o}^{1} \mathbf{V}}\right]$	8.31432
	Dry Air Gas Constant	$R_{\rm d}$	$[J/(kg \cdot K)]$	287.058
ŀ				
	Water Vapor Gas Constant	$R_{\rm v}$	$\left[J/\left(kg\cdot K\right) \right]$	461.495

the whole year on average detailing each season. According to the initial expectations, the biggest amount of resources the mobile base station is able to obtain from solar radiation is the summer solstice (572.64), where the peak value of the energy production process is also the highest (91.86). The ranking was followed by vernal and autumn equinoxes and winter solstice. Hence, there could be seen that in terms of the reduction of energy delivered by the conventional sources (i.e., from the batteries, which are charged up from the dedicated stations) the order is adequate to the aforementioned dependencies (middle array). However, due to the limitations related to the number of PV cells as well as their efficiency of power generation, the maximal achieved energy gain was equal to 5.8% (summer solstice). It is also valid to be noticed that during the winter solstice, this gain is almost none (0.18%). Finally, the bottom array indicates the average number of UAV BS replacements, when its battery is gone. Due to weather conditions, the variety of this number can even be observed when are no RESs engaged to power up the mobile access node. The highest number of exchanged drones very noticed for summer solstice (13.93) and next for autumn equinox (13.39), winter solstice (13.28), and vernal equinox (13.24), respectively. On the contrary, when the UAVs are supported by PV panels, summer solstice as well as vernal equinox needs the lowest average number of replacements (12.98). Taking into account the fact that during the summer the energy demand of a single UAV BS increases compared to other seasons of the year, this confirms the above-described results related to the profit when generating resources from solar radiation at this time. Thus, due to the almost zero impact of using PV arrays in winter solstice on power consumption characteristics, the number of UAV replacements is the same for both cases, i.e., with and without enabled RESs.

TABLE III ENERGY CHARACTERISTICS FOR UAV BSS WITH AND WITHOUT RESS

	Total (and peak) energy obtained from PV Panels per UAV [Wh]		
	No RESs	PV Panels	
Vernal Equinox	0 (0)	475.17 (60.57)	
Summer Solstice	0 (0)	572.64 (91.86)	
Autumn Equinox	0 (0)	349.56 (65.15)	
Winter Solstice	0 (0)	17.67 (4.18)	
Annual average		353.76	

	Average reduction in energy consumption (AREC) [%]		
	No RESs	PV Panels	
Vernal Equinox	0	4.89	
Summer Solstice	0	5.8	
Autumn Equinox	0	3.56	
Winter Solstice	0	0.18	
Annual average		3.61	

	Avarege number of UAV replacements (ANUR)	
	No RESs	PV Panels
Vernal Equinox	13.24	12.98
Summer Solstice	13.93	12.98
Autumn Equinox	13.39	13.09
Winter Solstice	13.28	13.28
Annual average	13.46	13.08

V. CONCLUSIONS

The contribution presented in this paper highlights the advantages related to the use of PV panels as power generators in cellular networks equipped with UAVs as mobile access nodes and supported by RISs. For the considered scenario, due to the weather conditions prevailing in Poland as well as the assumed configurations of UAVs and RESs, the power savings (and the resulting financial ones) are equal to the level of 3.61% per year on average in comparison to the case,

in which base stations of the wireless system are supplied only from the charging stations powered by the conventional energy grid. Although RESs like PV panels are characterized by time-varying and climate-dependent harvesting processes, by appropriate management of available resources (radio and energy) using optimizing algorithms (e.g., traffic steering, resource allocation, etc.) and enabling additional equipment like RIS arrays, we are able to improve already achieved results or even ensure energy autonomy for cellular network without worsening the quality of mobile services delivered to users. However, the implementation of those algorithms as well as studies focused on the impact of RIS on radio signal propagation will be taken into consideration in future work.

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