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Link budget estimations for millimeter-wave links via anomalous reflectors

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***Abstract*—High-frequency (millimeter-wave) wireless communications require the use of directive, high-gain antennas, as otherwise the achievable length of the communication link quickly decreases with increasing frequency. In order to provide necessary space coverage, anomalously reflecting and reconfigurable intelligent surfaces can be possibly used. In this presentation, we will discuss our recent results on analytical estimations of the link budget in the presence of such reflectors. Using the concept of macroscopic reflection coefficients, it is possible to come to very simple analytical expressions for the far field and set it into the form of a generalized Friis formula. The analytical results are validated by numerical simulations of a particular realization of an anomalous reflector for the millimeter-wave frequency band.**

***Index Terms*—reconfigurable intelligent surface, link budget, millimeter-wave communications, metasurface, anomalous reflection.**

I. Introduction

One of the fundamental relations in the theory of wave propagation, the Friis formula

$$P_{\rm R} = G_{\rm T} G_{\rm R} \frac{\lambda^2}{4\pi r^2} P_{\rm T} \tag{1}$$

defines the power $P_{\rm R}$ received via a free-space link in terms of the transmitted power $P_{\rm T}$, distance between the transmitter and receiver r, gains of the two antennas $G_{\rm T}$ and $G_{\rm R}$, and the wavelength λ. The always increasing need to transfer more and more data demands the use of higher and higher frequencies (smaller and smaller wavelength), but this formula reveals a problem: the received power decays as λ^2, if all the other factors remain the same. And if resonant and matched antennas are used, the antenna gain is practically independent from the resonance frequency, meaning that the received power indeed drops as λ^2 when the operational frequency increases. An obvious solution is the use of directive antennas. Indeed, if the antenna aperture is large compared to the wavelength, the effective aperture $A_{\rm eff}$ is close to the geometrical aperture A, and the antenna gain $G = A_{\rm eff}\frac{4\pi}{\lambda^2}$ of an antenna of a certain size *increases* with decreasing wavelength as $1/\lambda^2$, compensating the decaying factor in the Friis formula.

However, the propagation scenario becomes dramatically different: instead of sending signals using weakly directive antennas into a naturally multi-path environment, highly directive beams are sent towards receivers. Possible solutions for non-line-of-sight links can be the use of anomalously reflecting and reconfigurable intelligent surfaces (RIS). Importantly, these surfaces are electrically large reflectarray antennas, whose gain is also increasing with the frequency, according to the same formula $G = A_{\rm eff}\frac{4\pi}{\lambda^2}$. They function as highly directive repeaters, further increasing the received power at high frequencies.

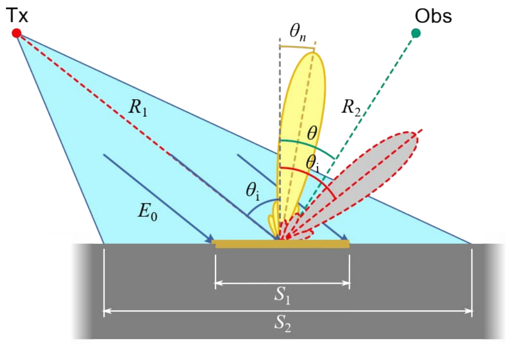

Fig. 1. Anomalous reflector mounted on a uniform wall and illuminated by a focused beam.

The typical high-frequency scenario with the use of RIS is illumination of a finite-size reconfigurable panel located on a uniform wall by a directive beam coming from a transmitting antenna, as illustrated in Fig. 1. Interestingly, the illuminated spot of a uniform wall also acts as a directive reflectarray antenna (with the reflected beam in the specular direction). Thus, in this scenario the reflected and scattered field is created by *two* directive reflectors: one is the metasurface that creates a directive beam in the desired direction, and the other is the reflecting wall, sending energy predominantly in the specular direction. The two reflected beams interfere in the domain of overlapping sidelobes.

Here, we present simple analytical estimations for link budget (generalized Friis formula) for this high-frequency communication scenario and discuss some properties of the reflected fields.

II. Link-budget estimations

We consider anomalous reflectors realized as periodical structures with the period D defined based on the design incidence angle and the desired anomalous reflection angle. The theory is limited to surfaces for anomalous reflection in one plane. Thus, the surface is uniform in the direction normal to the incidence plane. To estimate the reflected fields in the far zone we use the analytical results presented in [1], [2]. The electric field scattered into the far zone can be approximately written as

$$E_{\rm sc}=\frac{jk}{4\pi}\frac{e^{-jk|\mathbf{r}|}}{|\mathbf{r}|}E_0\Bigg[S_2\Bigg((1+\Gamma_{\rm wall})\cos\theta - (1-\Gamma_{\rm wall})\cos\theta_{\rm i}\Bigg)\text{sinc}(ka_{\rm ef}) + S_1\sum_n(\Gamma_n-\Gamma_{\rm wall}\delta_n)(\cos\theta+\cos\theta_n)\text{sinc}(ka_{\rm ef\it n})\Bigg]. \tag{2}$$

Here, $\mathbf{r}$ is the radius-vector from the metasurface to the observation point, E_0 is the amplitude of the incident electric field at the metasurface location, $S_2=a_2^2$ is the area of the illuminated spot, $\Gamma_{\rm wall}$ is the reflection coefficient of the wall, θ is the observation angle, $\theta_{\rm i}$ is the incidence angle, $S_1=a_1^2$ is the area of the metasurface, Γ_n are the macroscopic reflection coefficients [2] for the propagating Floquet harmonics reflected at the angles θ_n, δ_n is the Kronecker delta, and the effective widths of the metasurface and the illuminated spot are given by $a_{\rm ef}=(\sin\theta-\sin\theta_{\rm i})a_2/2$, $a_{{\rm ef}n}=(\sin\theta-\sin\theta_n)a_1/2$.

Assuming that the metasurface design ensures that parasitic reflections into undesirable propagation modes are negligible, we include only the contribution of the main anomalously-reflected Floquet harmonic (order $n=-1$). That is, the surface is designed to anomalously reflect obliquely incident waves into the desired direction (with an arbitrary tilt in the incidence plane). Furthermore, we consider the case when the receiver position is at the direction of anomalous reflection from the metasurface ($\theta=\theta_{-1}=\theta_{\rm r}$) and neglect the sidelobe contribution from uniform-wall reflections at the receiver position. Under these simplifying conditions, we can derive a generalized Friis formula for a receiver placed at the direction of the main anomalously reflected beam. To do that, we first substitute the value of the incident field E_0 as a function of the transmitted power $P_{\rm T}$, transmitter antenna gain $G_{\rm T}$, and the distance between the transmitting antenna and the metasurface R_1. Next, we express the received power $P_{\rm R}$ in terms of the field at the receiver position $E_{\rm sc}$ (2), located at a distance $r=R_2$ from the metasurface, and the receiver antenna gain $G_{\rm R}$. The result reads

$$P_{\rm R}=P_{\rm T}G_{\rm T}G_{\rm R}\frac{\lambda^2}{(4\pi R_1R_2)^2}G_{\rm M}, \tag{3}$$

where

$$G_{\rm M}=\eta_{\rm eff}\left(\frac{S_1}{4\pi\lambda}\right)^2\cos\theta_{\rm i}\cos\theta_{\rm r}. \tag{4}$$

Parameter $\eta_{\rm eff}$ is the efficiency of anomalous reflection into the desired direction.

The value $G_{\rm M}$ has the meaning of gain of the anomalous reflector of the metasurface acting as a directive repeater. As expected, we see that this metasurface gain scales as $1/\lambda^2$, compensating the frequency factor in the conventional Friis formula.

III. Numerical validation

We have tested the simple approximate analytical formula for the link budget for an anomalous reflector designed to reflect TE-polarized waves at the incidence angle $\theta_{\rm i}=50^\circ$ into the normal direction ($\theta_{\rm r}=0$) for the operational frequency 144.75 GHz. The structure contains three layers: a PEC ground plane, a dielectric layer with $\epsilon_r=4.2$ (quartz), and a patterned metal layer modeled by its sheet impedance. The dielectric substrate has the thickness $h_{\rm sub}=209.5$ μm. In accordance with the diffraction grating theory, the period of the structure to allow the desired functionality at the first diffraction mode should be set to $D=\lambda_0/\sin(\theta_{\rm i})\approx 2705.5$ μm. The supercell was split into 8 sub-cells, and the reactive sheet impedances of the sub-units were collectively optimized to achieve the desired performance, using the procedure described in [3]. For simplicity of calculations, we have neglected dissipation losses in the structure, as they can be simply accounted for in the value of $\eta_{\rm eff}$.

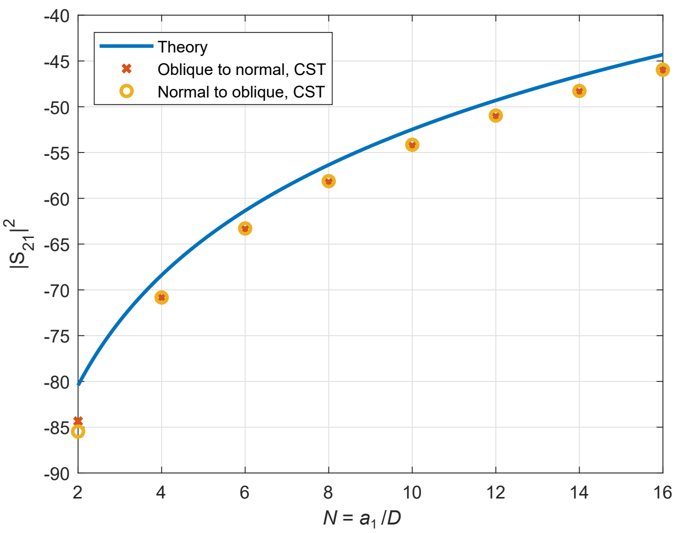

Fig. 2. Validation of the link-budget model. Comparison between the theoretical link-budget formula (3) and numerical results (CST). The horizontal axis shows the normalized metasurface size, defined as the number of metasurface supercells N over its width a_1. On the vertical axis we show the power transmission coefficient $|S_{21}|^2=P_{\rm R}/P_{\rm T}$ in dB. In this example, the gains of both antennas $G_{\rm T}=G_{\rm R}=23.8$ dB, and the separation distances $R_{1,2}=1000\lambda$.

The structure was simulated using CST Studio Suite software. Simulations of an infinite periodical metasurface predict $\eta_{\rm eff}=99.99\%$ efficiency of the anomalous reflection. Finite-size structures were simulated for different normalized sizes of the metasurface, defined by the number of supercells $N=a_1/D$. Anomalous reflectors were illuminated by a horn antenna in the far-field region ($R_{1,2}=1000\lambda\approx 2.07$ m) with directivity 23.8 dB. Therefore, in order to correctly simulate realistic illuminations from the distanced source and complex electromagnetic response of electrically large samples with sub-wavelength features we applied the so-called hybrid assembly simulation combining the method of moments (integral equation solver) and the finite element method (frequency solver). Semi-analytical simulations allowed us to estimate transmission between two horn antennas via reflection from a finite anomalously reflected panel. The comparison of the analytical estimation based on (3) and numerical results are presented in Fig. 2, confirming the model validity.

IV. Conclusion

In this abstract, we presented a simple link-budget estimation formula for the case when the link is provided via anomalous reflection in a periodical metasurface, and the main reflected beam is directed exactly towards the receiver position. The far-field scenario was assumed, and scattering from the illuminated part of the uniform wall towards the receiver was neglected. In the conference, we will also present results for the case of an arbitrary position of the receiver and discuss the effects of scattering from the illuminated spot on the uniform wall. Also, we will discuss the effects of non-uniform spot illuminations.

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