Twisted Radio Waves and Twisted Thermodynamics

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Abstract. We show that the assumption that, at a single frequency, more than two independent information channels can be provided by an antenna violates the Second Law of Thermodynamics, and thus this assumption cannot be correct.

Recently it has been claimed in scientific literature and popular news media—and purportedly demonstrated by experiment—that it is possible to generate radio waves with more spatially orthogonal "orbital" modes than the usual two polarization modes [1-4]. Such radio waves would have angular momenta (so called orbital angular momenta) different from the angular momentum of circularly polarized waves in a similar way as the orthogonal (l) wave modes of electrons belonging to the same main quantum number (n) exist at the same frequency. Communication utilizing such independent/orthogonal modes would expand the available frequency band by a factor given by the number N of such spatially orthogonal modes. Experimental demonstration for $N = 2$, which is equal to the number of modes of a standard circularly polarized wave, has been carried out and published [2]. If the number of spatially orthogonal modes can be more than two, or even infinite as claimed in news media [1], this would revolutionize wireless communication because the information channel capacity of the radio waves scales linearly with N in the case of fixed bandwidth and signal-to-noise ratio.

It is important to note that, recently, independent groups with expertise about antennas/propagation published two papers [5,6] that are strongly criticizing the twisted radio waves concept. Both papers [5,6] conclude that the proposed twisted wave schemes belong to the traditional *multiple-in-multiple-out* (MIMO) technique thus they are not conceptually new. Furthermore [5], among others, points out that, in the far field, such scheme provides no information channel capacity gain. Paper [6] shows that the experiments [2] have not been performed in "far-enough-field" conditions. A real far field wireless situation would imply further losses and other deficiencies [6].

At the fundamental physics side, which is our top concern, the most important question before the idea of a vastly increased capacity for radio communication can be realized in practical applications is whether such "orbital" modes can really be utilized independently from the basic plane wave modes of the regular wireless communications. If the polarization is circular—a common situation in wireless technology—one has $N = 2$ and the waves in the two polarization modes are phase-shifted by 90^o, which leads also to non-zero angular momentum. Thus the situation with $N = 2$ is obvious because of the existence of the two polarization modes and the circularly polarized plane waves.

It should first be noted that an assumption of more than the two *far-field* polarization modes is counter-intuitive. In the atom, the existence of waves with different angular momenta at the same energy originates from the potential and the ensuing localized nature of the waves. A charge revolving in a Coulomb potential field will have an infinite number of different classical physical paths with the same energy, and Bohr-Sommerfeld quantization will select a finite number of states that are allowed within quantum theory. But, in stark contrast, no such state components exist for free electron waves. In the light of this intuitive argument, the existence of spatially orthogonal modes for electromagnetic waves is fine for photons propagating under spatially confined conditions such as in wave guides and optical fibers [7,8], or in the immediate surroundings of a black hole [9]; however it is difficult to imagine them in the free space propagating independently from classical plane waves. Thus the ultimate question for possible applications in wireless communication [1,2] is this: Can modes with non-zero angular momenta, beyond the N=2 trivial case, be radiated and selectively picked up by a proper antenna, which is insensitive for standard plane wave modes to represent extra, independent communication channels? We reiterate that the existing experimental radio wave demonstrations [2] hold only for $N = 2$.

Rather than analyzing the theoretical treatments for errors, we use another approach and prove that the hypothesis that these orbital modes can selectively be picked up by a proper antenna, which is insensitive for standard plane wave modes to represent extra, independent communication channels would violate the Second Law of Thermodynamics that states the impossibility of constructing a perpetual motion machine of the second kind. First let us specify the necessary conditions that are essential for the utilization of the M-th orbital mode as a parallel independent information channel:

i) A selective antenna must exist that is able to radiate in the M-th orbital mode.

ii) The same antenna should selectively pickup signal from an electromagnetic wave only at the M-th orbital mode while discarding all the other orbital and non-orbital mode components in that electromagnetic wave.

According to Planck's Law [10], the a black-body (with unity emissivity) radiates in each polarization with a power spectral intensity

$$I(f) = \frac{4\pi h f^3}{c^2} \frac{1}{e^{hf/kT} - 1} \quad , \tag{1}$$

where f is frequency, $h = 6.626 * 10^{-34}$ Js is Planck's constant, $k = 1.381 * 10^{-23}$ JK^{-1} is Boltzmann's constant and T is absolute temperature. This means that a unit surface area of the black-body emits, in each polarization, the power

$$P(f, \Delta f) = I(f)\Delta f = \frac{4\pi h f^3}{c^2} \frac{\Delta f}{e^{hf/kT} - 1} \tag{2}$$

within an infinitesimally small frequency band Δf around f. Thus the total radiated power from a unit area is

$$NP(f, \Delta f) = NI(f)\Delta f = N \frac{4\pi h f^3}{c^2} \frac{\Delta f}{e^{hf/kT} - 1} \quad , \tag{3}$$

where N=2 is the number of orthogonal polarization modes. Thus the Planck formula [10], is:

$$P(f,\Delta f)=\frac{8\pi hf^3}{c^2}\frac{\Delta f}{e^{hf/kT}-1} \quad . \tag{4}$$

Inspired by Nyquist's treatment of Johnson noise [11], we now devise the following gedanken experiment: A large box (much larger than the wavelengths considered) is located in a thermal reservoir of temperature T. We assume that its internal walls are ideally black. Furthermore an isolated resistor (with radiation screening and thermal isolation) and a "twisted-wave" antenna tuned to the *M*-th orbital mode in a bandwidth of Δf around frequency f are in the box and the resistor is connected to the electrodes of the antenna. We start from thermal equilibrium, *i.e.*, a uniform temperature within the box, including the walls, the inherent thermal radiation, the antenna, the resistor, and the thermal isolation/screening.

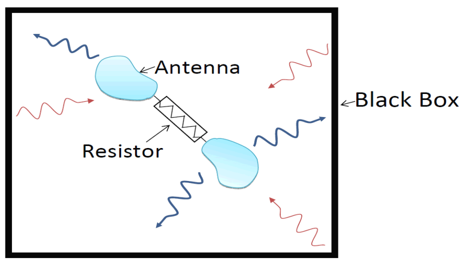

Figure 1. Outline of the gedanken experiment

Conditions *i*) and *ii*) will result in the following situation:

a) In accordance with condition *i*), the energy supplied by the resistor will be radiated by the antenna in the *M*-th orbital wave mode. This energy will be absorbed in the walls. The wall will emit thermal radiation in the form of plane waves [10] with power density spectrum satisfying Eq. 4.

b) In accordance with condition *ii*), the antenna can pickup signal only at the *M*-th orbital mode while will discard all the plane wave components radiated by the walls of the box. That means, this antenna will not pick up any signal because the walls emit only plane waves [10].

Thus the energy will flow out from the resistor and it cannot return there thus the situation cannot satisfy Boltzmann's Principle of Detailed Balance [12]. The resistor will cool down, which implies that a temperature inhomogeneity is induced in the system in thermal equilibrium and hence violates of the Second Law of Thermodynamics.

The only way to avoid the violation of the Second Law of Thermodynamics with the mentioned set-up is to suppose that the antenna picks up also the plane wave modes thus it cannot not offer a separate information channel for the orbital mode.

It should also be mentioned that it is well-known that the corresponding antenna types that can emit circularly polarized waves (which also have non-zero angular momentum) are all sensitive for plane waves because a plane wave will excite their relevant polarization mode. Thus a circular polarization antenna will not violate the Second Law when it is use in the same gedanken experiment as described above.

In conclusion, our fundamental physical results are in agreement with the relevant conclusions of papers [5,6]. Specifically, we have shown that the assumption that, at a single frequency, more than two information channels — carried by the actual polarization modes — can be provided by an antenna violates the Second Law of Thermodynamics, and thus this assumption cannot be correct. If some experiment appears to support an assumption that violates a Law of Physics, then *either* the experiment and/or its interpretation is incorrect *or* that particular Law of Physics is invalid for the situation in case.

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