POLICY RESEARCH MEMORANDUM | MARCH 2026

Toward a Biological Fidelity Act

Defining a protected electromagnetic and optical habitat for long-dwell human environments, with a focus on low-frequency temporal structure, harmonics, pulsing, light timing and modulation, and transition pathways toward wired, optical, and low-ripple power systems.

Core conclusion
The present literature does not justify a simple list of universally forbidden carrier frequencies. It does justify a more defensible policy move: protect the low-frequency temporal structure of occupied electromagnetic environments and the timing / modulation structure of occupied optical environments, especially in long-dwell interiors such as homes, bedrooms, schools, day-care settings, maternity care, hospitals, and offices where people spend many hours a day.

Question	Bottom line	Transition path
What part of the electromagnetic environment should be treated as protected habitat for high-fidelity biology?	Protect the low-frequency temporal habitat band first; regulate placement, duty cycle, harmonics, pulsing, and optical timing / TLM before chasing single carrier bans.	Fiber and wired first; daylight-friendly, circadian-sane, low-TLM optical wireless where needed; pilot low-ripple DC interiors rather than assuming AC is the only default.

Executive summary

- 1. The strongest evidence signal is not a single forbidden wireless carrier. It is the combination of chronic dwell time, proximity, time variation, power-frequency magnetic fields, harmonics, pulsing, low-frequency envelope content, and - for lighting systems - inappropriate timing, spectrum, and temporal modulation.
- **2.** The most defensible candidate for special legal protection is a protected temporal habitat band: 0 Hz-100 kHz inside long-dwell occupied environments, with immediate attention to 50/60 Hz magnetic fields and their harmonics, and with adjacent precautionary scrutiny for 100 kHz-1 MHz emissions from power electronics and wireless power systems.

- 3. Current public limits were built mainly to prevent established acute effects such as nerve stimulation, shock, and tissue heating. They are not a finished answer for chronic developmental, reproductive, circadian, or multi-generational exposure questions. A Biological Fidelity Act would supplement heat-based compliance with fidelity-based habitat design.
- **4.** A Biological Fidelity Act should therefore regulate environments by occupancy class and temporal structure, not only by carrier frequency. Homes, bedrooms, schools, NICUs, maternity wards, hospitals, prisons, dormitories, and offices where people remain more than eight hours per day should be treated as protected electromagnetic habitat.
- 5. The transition path should be fiber and wired Ethernet as the default communications backbone, optical wireless only when it is both low in temporal-light-modulation burden and compatible with proper light at the proper time, and pilot low-ripple direct-current interiors in sensitive spaces. Indoor RF should become a constrained fallback layer rather than the default environmental background.
- 6. Because the science is still incomplete, the proposed statute should not pretend to have already discovered the final hazard map. It should instead create a federal measurement, standards, and research program that can identify biologically relevant low-frequency modulation, harmonics, duty cycle, burstiness, dwell-time thresholds, and optical timing and modulation targets.

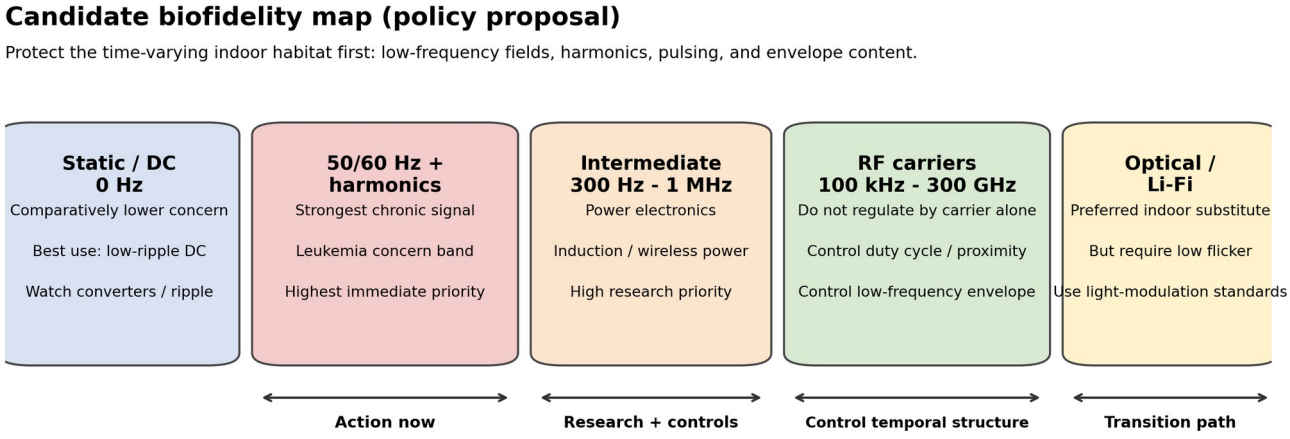

Figure 1. Candidate biofidelity map. This is a policy inference from the current literature, not a settled hazard chart.

1. What the evidence actually supports

What can be said now	What cannot be said yet
There is a credible case for treating chronic low-frequency magnetic fields, harmonics, and modulation/envelope content as a distinct	The literature does not yet supply a universal table of safe and unsafe frequencies for all carriers and all modulations. It does not

regulatory concern in long-dwell interiors. There is also a credible case that current acute-effect standards do not fully answer developmental or chronic-dwell questions.	justify claiming that one specific wireless pulse rate or one RF carrier is the single cause of modern cognitive, behavioral, or civilizational trends.

The policy problem here is not whether every EMF source is equally dangerous. It is whether modern regulation is asking the right question. Most current public limits were built around established acute effects - shock, nerve stimulation, and tissue heating - while the user-facing question is different: what kind of electromagnetic habitat should be preserved for chronic, developmental, prenatal, reproductive, and multi-generational life in places where people live for long periods?

That distinction matters because the best-supported chronic concern in the literature is not a broad proof that all radiofrequency exposure below present limits is harmful. The clearest long-running signal is the epidemiologic association between residential power-frequency magnetic fields and childhood leukemia in the neighborhood of average exposures above about 0.3-0.4 microtesla, even though more recent pooled work has weakened that association and the causal interpretation remains disputed. This means the evidence is mixed - but it does not mean the chronic-exposure question has been answered.

Likewise for RF systems, the strongest recent animal evidence is not mirrored by equally strong human evidence. Recent WHO-commissioned human observational reviews reported mostly null or very uncertain findings for major tumor outcomes, cognition, and male fertility, while recent experimental-animal reviews reported high-certainty evidence for some cancers in male rats and low-to-moderate certainty signals for some reproductive and developmental endpoints. That asymmetry is exactly why a habitat-protection framework is more defensible than a blanket claim of settled safety or settled catastrophe.

1.1 Power-frequency magnetic fields are still the first place to act

The World Health Organization still summarizes the key long-term concern for extremely low frequency magnetic fields as childhood leukemia, reflecting IARC's classification of ELF magnetic fields as 'possibly carcinogenic to humans' based on limited human evidence and less than sufficient animal evidence. WHO also reports that average residential power-frequency magnetic fields are far below transmission-line hotspots - roughly 0.07 microtesla in Europe and 0.11 microtesla in North America - but that the pooled analyses which drove the IARC classification focused on average residential exposures above about 0.3-0.4 microtesla (WHO 2007 fact sheet; IARC framing).

Recent syntheses keep the signal mixed rather than resolved. Brabant et al. (2022) concluded that ELF magnetic fields above 0.4 microtesla may increase childhood leukemia risk, while Amoon et al. (2021) pooled more recent studies and found the excess risk had declined to no association, possibly because of methodological issues, random chance, or a true change over time. For policy,

the key implication is not that a medical threshold has been proven. It is that chronic indoor magnetic fields in the few-tenths-of-a-microtesla range deserve explicit design attention in sensitive spaces.

That is a striking mismatch with present low-frequency public reference levels. The ICNIRP low-frequency guidelines use reference levels of 200 microtesla for the general public at 25-400 hertz, because those guidelines were derived to protect against established acute effects such as stimulation. A habitat-based law would not replace those acute limits; it would supplement them with chronic-dwell design targets that are orders of magnitude lower.

1.2 Intermediate-frequency emissions are a major research and precaution gap

The intermediate-frequency region - roughly 300 hertz to 1 megahertz - is where modern power electronics, induction devices, wireless power transfer, EV charging infrastructure, switching power supplies, and related 'dirty electricity' questions start to crowd together. This is precisely the part of the spectrum that has grown rapidly in real buildings while remaining comparatively under-investigated.

A systematic review by Bodewein et al. (2019) found the quality of evidence for adverse effects of intermediate-frequency fields remained inadequate for drawing conclusions for most endpoints because studies were heterogeneous, many were methodologically limited, and most investigated field strengths above public reference levels. The review explicitly recommended more systematic study across multiple frequencies and field strengths, especially where threshold-dependent effects might exist. A later review by Lee et al. (2023) similarly concluded that most IF studies suggest no harm, but some adverse effects have been reported during developmental stages and prolonged exposure.

This is why a Biological Fidelity Act should not wait for perfect certainty before acting. The intermediate-frequency domain is exactly where modern building electrification, wireless power, and switching infrastructures can create persistent low-frequency electromagnetic structure inside occupied spaces. At minimum, that band belongs in a national mapping and measurement program.

1.3 RF evidence points more to temporal structure than to a single forbidden carrier

For RF systems, the present literature does not justify a simple carrier blacklist. Recent human observational reviews found no increased risk of the most studied adult tumors, pediatric brain tumors, childhood leukemia from fixed-site transmitters, or several less-studied cancer outcomes in relation to mobile phone use, although these studies remain limited by exposure assessment and other biases. Recent human reviews on cognition found very low- to low-certainty evidence of little to no association, and the human evidence on male fertility from mobile phone exposure remained very uncertain.

At the same time, the animal literature is materially less reassuring. A 2025 systematic review of experimental-animal cancer studies judged the certainty of evidence high for glioma and malignant heart schwannoma in male rats exposed to RF fields. A 2025 review of pregnancy and birth outcomes in experimental mammals concluded that in utero RF exposure likely affects some birth outcomes, but the body of evidence did not allow the authors to determine whether such effects occur below levels that cause known heating. A 2024 review of male fertility in experimental animals found moderate certainty for reduced pregnancy rate and low certainty for reduced sperm count, while also emphasizing that most studies were methodologically limited and often at exposure levels above typical human conditions.

Mechanistically, this means the best policy target is not 'ban frequency X.' What deserves scrutiny is the low-frequency content that rides on or accompanies many high-frequency systems: pulse repetition, amplitude envelope, harmonics, duty cycle, burstiness, and random low-frequency variability. Panagopoulos et al. (2025) argue that wireless communication signals are biologically distinctive because microwave carriers are combined with ELF or VLF modulation and ULF variability; that argument remains disputed, but it is useful as a hypothesis-generating framework for regulation because it points directly to measurable temporal structure rather than only to carrier frequency.

The older modulation-specific review literature is also consistent with caution rather than certainty. Juutilainen et al. (2011) concluded that most studies reported no modulation-specific effects, but a few notable exceptions suggested that amplitude-modulated RF could have specific effects on the human central nervous system and warranted further follow-up. That is not enough to legislate a final list of forbidden pulse rates. It is enough to say that the temporal signature of wireless exposure belongs inside the regulatory question.

1.4 Static fields and direct current should be treated differently from AC and RF

The evidence base for static fields looks different. A systematic review of static electric fields concluded that the weight of evidence did not indicate adverse biological effects in humans or animals and that direct internal physiological effects are physically implausible at ordinary exposure conditions. A separate review of weak static magnetic fields found the evidence insufficient to draw conclusions either way because the literature is sparse and methodologically weak.

That matters because it makes direct-current architecture worthy of pilot projects rather than immediate dismissal. Direct-current microgrids can reduce conversion losses, may offer superior power quality, are usually devoid of 60 hertz harmonics, and are buffered from some grid events; however, modern DC buildings still use converters and can contain intricate power-electronic networks. So the right proposal is not 'all DC is automatically safe.' The right proposal is 'pilot low-ripple DC interiors with explicit limits on ripple, converter noise, switching transients, and stray magnetic fields.'

1.5 The optical habitat has to be specified by timing, spectrum, intensity, and modulation

For visible light, the right biological-fidelity rule is not 'blue light is bad.' It is that delivered light exposure depends on timing, intensity, spectrum, duration, and the state of the person receiving it. CIE's current position is explicit that the effect of light comes from the combination of light level and spectrum together, that different light sources in the immediate environment add together, and that correlated colour temperature by itself can be misleading. In policy terms, the optical habitat has to be specified at the eye, not guessed from a lamp label.

That yields a simple design principle for protected occupancies: make strong daytime light exposure and daylight access easy; reduce melanopic exposure substantially in the evening; and keep sleep environments near-dark except for task-critical care events. CIE's current public-facing guidance for healthy adults points toward high daytime melanopic EDI, a much lower level for the three hours before bedtime, and very low overnight exposure during sleep, while also warning that real spaces usually need controllable ranges rather than one universal fixed value.

Temporal light modulation is a separate constraint, not a footnote. DOE and IEEE document that LED and OLED systems can generate waveforms whose shape, modulation depth, duty cycle, and frequency matter for direct flicker, stroboscopic effects, and phantom-array effects, and DOE notes that visible artifacts can persist well into the kilohertz range for some observers. That means a Biological Fidelity Act should regulate not only spectral content but also the time structure of emitted light.

Li-Fi therefore has to be split into two categories. Visible-light systems, especially those integrated with room illumination, must satisfy both communications objectives and optical-habitat rules. Near-infrared light communications are different: IEEE 802.11bb specifies light communications in the 800 nm to 1000 nm band, which can reduce visible-light burden, but such systems still need photobiological-safety, beam-geometry, and occupancy-proximity constraints. The law should never assume that 'invisible' means 'biologically irrelevant'; it should specify which biological question is being controlled.

2. The protected biofidelity zone proposed here

The most defensible way to define a biological quiet zone from the present evidence is to stop thinking like a spectrum auction and start thinking like habitat protection. The protected object is not an isolated carrier band. It is the low-frequency temporal habitat inside occupied space: the slowly varying, pulsed, harmonic-rich field structure that people experience continuously while sleeping, learning, gestating, and working.

Tier	Candidate band	Why it matters	Proposed posture
Tier 1	0 Hz - 100 kHz	Contains static fields, 50/60 Hz power-frequency fields, harmonics, and much of the low-frequency modulation or envelope content that rides on communication and power systems.	Treat as protected indoor habitat band in long-dwell spaces.
Tier 2	100 kHz - 1 MHz	Transition region between low-frequency guidelines and RF systems; increasingly populated by power electronics, induction, and wireless-power technologies.	Map, monitor, and apply precautionary engineering controls.
Tier 3	RF carriers > 100 kHz	Carrier frequency alone is not the best predictor of chronic bioactivity; temporal structure, duty cycle, proximity, and dwell time matter.	Allow conditionally, but regulate envelope content, placement, and duty cycle.
Preferred substitution path	Optical / wired	Fiber and wired links avoid continuous RF occupation of indoor space; optical links can support mobility when designed for low flicker.	Use as procurement and building-code default in protected spaces.

Tier 1 - 0 Hz to 100 kHz - is the key proposal. This is not because every frequency in that band has already been shown to be harmful. It is because the strongest current chronic signal sits within it, much of the relevant pulsing and harmonics sit within it, and the present legal regime is least adapted to asking biological questions about it.

Proposed legal definition

Protected biofidelity zone: an occupied electromagnetic environment in which avoidable low-frequency temporal variation, power-frequency magnetic fields, harmonics, intermediate-frequency emissions, and communication-envelope structure are minimized to the greatest extent feasible consistent with the function of the space, with the strictest requirements

applied to prenatal, early-life, sleep, health-care, and long-dwell settings.

2.1 What would count as acceptable, constrained, and unacceptable by default

Because the science is incomplete, this paper uses a zoning logic rather than a claim of absolute proof. The law should distinguish between what is acceptable by default, what is acceptable only with constraints, and what should be disfavored or prohibited in protected spaces when feasible alternatives exist.

Acceptable by default	Acceptable only with constraints	Disfavored / prohibited in protected spaces
Fiber, wired Ethernet, shielded fixed cabling, daylight-friendly low-TLM optical links, and visible lighting that can meet day / evening / sleep optical-habitat schedules.	Indoor RF as a fallback or overlay layer; AC distribution when branch-circuit fields and harmonics are deliberately controlled; DC interiors only when ripple and converter noise are specified and tested; visible-light networking only in spaces where timing and TLM can be actively managed.	Always-on high-duty-cycle RF transmitters near beds, cribs, desks, or patient bays when wired or optical alternatives are feasible; new protected interiors designed with chronic 50/60 Hz magnetic fields in the epidemiologic concern range; bright visible-light networking in sleep zones; wireless power and induction emitters placed close to sleep or prenatal zones.

3. How to codify a quiet zone without pretending the science is already finished

A statute can act before final threshold science is complete by making two moves at once. First, it can adopt interim design rules in the spaces where chronic biological fidelity matters most. Second, it can mandate a federal research and standards program to replace those interim rules with validated exposure metrics over time.

3.1 Provisional design bands for 50/60 hertz magnetic fields

For power-frequency magnetic fields, the law should be explicit that interim bands are policy tools, not proven medical thresholds. The present literature is strongest around the few-tenths-of-a-microtesla range, while current acute-effect limits sit orders of magnitude higher. That makes it reasonable to create an interim chronic-dwell design framework centered on measured long-term magnetic-field conditions in occupied rooms.

Band	Average field	Interpretation	Recommended code response
Preferred	< 0.1 μT	Research-oriented target for bedrooms, nurseries, maternity care, classrooms, and other protected long-dwell rooms.	Use as preferred design goal for new builds and renovations.
Watch	0.1 - < 0.3 μT	Below the historic epidemiologic concern band but still worthy of mapping, source tracing, and harmonic control.	Document sources; correct avoidable wiring and equipment causes.
Action	0.3 - < 0.4 μT	Enters the range that informed IARC/WHO leukemia concern framing.	Mitigation plan required in protected spaces.
Not acceptable for new protected interiors	>= 0.4 μT	At or above the band most often used in pooled leukemia analyses.	Do not approve new protected rooms without redesign or shielding/relocation.

Important note: *These bands are proposed policy working levels derived from the epidemiologic literature and a precautionary design logic. They are not claimed here as proven biological thresholds.*

3.2 The central RF rule: regulate the envelope that occupies the room

The RF problem should be framed differently from the AC problem. In most long-dwell interiors, the law should not ask only whether a router, small cell, or device is below a thermal compliance limit. It should also ask what low-frequency temporal structure that system is adding to the room over hours, days, and years.

Accordingly, the first generation of the Act should avoid pretending to know the final forbidden pulse rates. Instead it should direct FCC, FDA/HHS, NIST, and NIEHS to create a standard measurement package for at least the following parameters: duty cycle; burst repetition rates; low-frequency envelope power in the 0.1 Hz-30 kHz region; harmonics; peak-to-average ratio; nighttime occupancy-adjusted exposure; and coexistence with ambient power-frequency fields.

This would move U.S. regulation away from a carrier-only mindset and toward an exposure-architecture mindset. It would also align the law with the specific defect identified by the D.C. Circuit in Environmental Health Trust v. FCC: the FCC had not adequately explained its treatment of long-term exposure, pulsation or modulation, children, pregnant women, and technological changes since 1996.

3.3 Why direct current should be piloted, not romanticized

The idea of sending more direct current into buildings is not fringe engineering; DC microgrids are a live area of building research. They can reduce conversion losses and are usually devoid of 60 hertz harmonics. That makes them attractive as a biological-fidelity experiment in sensitive interiors.

But a DC building is not a biologically solved building. Modern DC systems still depend on converters, controls, and power-electronic architecture. A law that simply swaps AC for unmanaged DC could replace one temporal structure with another. The prudent move is therefore to authorize federal demonstration projects for low-ripple DC interiors in hospitals, laboratories, dormitories, public housing, and schools, with mandatory measurement of ripple, transients, harmonics, and static stray fields.

3.4 The optical transition has to be written as low-flicker optical networking

Li-Fi is attractive because it can provide wireless mobility without filling the room with continuous RF carriers. But the transition has to be written as an optical-habitat rule, not as a generic 'more LEDs' rule. Where optical networking shares fixtures with general illumination, procurement should require CIE S 026-based eye-level metrics for timing and spectrum, measured temporal-light-modulation performance consistent with IEEE 1789 and current DOE / IES / CIE practice, and photobiological-safety compliance under IEC 62471.

That means protected occupancies should distinguish daytime task zones from evening and sleep zones. Day-active classrooms, offices, and clinical work areas may need strong daytime melanopic support and daylight access; bedrooms, nurseries, maternity wards, and overnight patient rooms need the opposite default: dim, low-glare, low-melanopic conditions and near-zero eyelid illuminance during sleep periods except when care tasks require temporary override.

Optical networking should also distinguish visible-light communication from near-infrared links. If the communications layer operates in visible light, the emitted waveform must be specified for both human lighting quality and data performance. If it operates in the 800 nm to 1000 nm band defined by IEEE 802.11bb, the main biological controls shift toward beam geometry, dwell time, and photobiological safety rather than circadian stimulation. Either way, the rule is the same: biological fidelity, not heat alone.

4. Draft architecture for a Biological Fidelity Act

The Act proposed here would have four operational parts: a habitat-protection title, a standards-and-measurement title, a building-and-procurement title, and a research title. The goal is to move from rhetoric to code: which spaces get protected first, which emissions get measured, which technologies are preferred, and which agencies must act.

4.1 Protected occupancies

Class	Occupancy type	Reason for elevated protection	Default technology rule
A	Pregnancy, birth, infancy, sleep, NICUs, maternity wards, nurseries, bedrooms	Highest developmental vulnerability and longest continuous dwell periods.	Wired / fiber / low-flicker optical by default; no always-on RF near beds or cribs.
B	Schools, day-care, libraries, dormitories, hospitals, prisons, eldercare	Long dwell, group exposure, limited individual control, public duty of care.	Wired and optical preferred; RF only where justified and spatially constrained.
C	Offices, laboratories, workshops, long-shift workplaces	Daily multi-hour exposure and occupational equity concerns.	Require measured field budgets and source control.
D	Transient public spaces, outdoor mobility corridors	Shorter dwell time and less need for stringent indoor habitat protections.	General RF service may continue subject to ordinary siting and exposure rules.

4.2 Federal measurement and standards program

The legal hook for such a program already exists in 21 U.S.C. 360ii, which directs the Secretary to establish an electronic product radiation control program, develop performance standards, study conditions of exposure to electronic product radiation and intense magnetic fields, and evaluate procedures for minimizing exposure. A Biological Fidelity Act should reactivate and modernize that authority instead of assuming new authority must be invented from scratch.

The first deliverable should be a Biofidelity Measurement Standard. Its job would be to define how indoor exposures are actually characterized in protected spaces. At minimum, it should require measurement of: static magnetic field; 50/60 hertz magnetic field; harmonics through at least 100 kilohertz; intermediate-frequency emissions through 1 megahertz; RF

power density or SAR proxies; low-frequency envelope spectra for wireless systems; temporal occupancy weighting; eye-level daytime / evening / nighttime melanopic EDI or successor CIE-compliant optical-habitat metrics; temporal-light-modulation metrics; and photobiological-safety class for visible and near-infrared optical systems.

> Conceptual measurement target: Biofidelity Index (BFI)
> BFI should be a composite score based on weighted measurement of power-frequency magnetic fields, harmonic content, intermediate-frequency emissions, RF envelope power in the low-frequency band, duty cycle, proximity to occupants, nighttime bedroom burden, daytime / evening / sleep optical exposure at the eye, temporal light modulation, and photobiological safety class for optical systems. The point is not to collapse all science into one number forever; it is to give building codes and procurement officials a workable instrument while the threshold science improves.

4.3 Building, procurement, and retrofit rules

Federal buildings and federally funded schools, housing, and health-care facilities should become the first proving ground. The law should require a technology hierarchy: fiber backbone first, wired local distribution second, low-temporal-light-modulation optical wireless third, and indoor RF last. Visible optical systems used for general illumination should meet circadian timing and night-protection rules; near-infrared links should meet photobiological-safety and conservative beam-placement rules. Where RF remains necessary, access points should be placed away from beds, cribs, patient bays, teacher stations, and fixed workstations, and their nighttime duty cycle should be minimized.

For power systems, new protected interiors should be commissioned with magnetic-field mapping, harmonic audits, and source-control plans. That means explicitly tracing transformer rooms, service entrances, subpanels, induction equipment, wireless chargers, EV charging hardware, and switch-mode supplies. The law should also require that sensitive rooms not share walls, floors, or ceilings with major electrical rooms without mitigation.

4.4 Optical habitat rules in protected occupancies

Protected occupancies should be required to maintain an eye-level optical exposure schedule, not just minimum work-plane illuminance. During daytime occupied periods, codes should favor daylight access and sufficient vertical-eye exposure to support alertness and circadian entrainment. During the three hours before habitual sleep, protected sleep and maternity spaces should automatically step down melanopic exposure and glare. During sleep periods, bedrooms, nurseries, dormitories, and overnight patient rooms should default to near-darkness, with task-directed exception modes only when needed.

All installed luminaires and optical networking devices in protected occupancies should disclose temporal-light-modulation performance under realistic dimming conditions. Procurement should prefer non-PWM or very-high-frequency strategies where feasible and should require measurement of direct flicker, stroboscopic risk, and phantom-array risk where applicable. Visible-light communications integrated into room lighting should be disfavored in sleep zones unless they can demonstrate both low TLM and low nighttime melanopic burden at the eye.

Near-infrared optical links should be permitted only with photobiological-safety certification and conservative beam-placement rules, particularly around cribs, beds, neonatal spaces, and fixed desks. The point is not to ban optical wireless. It is to ensure that the optical habitat is engineered with the same care now demanded for air quality, acoustics, and water.

4.5 Statutory amendments

Existing hook	Problem	Biological Fidelity Act move
47 U.S.C. 332(c)(7)(B)(iv) / Section 704	Localities may not regulate wireless facility siting on the basis of RF environmental effects when FCC rules are met.	Amend the clause so states and localities may apply health-protective biofidelity criteria in protected occupancies and zoning districts.
21 U.S.C. 360ii	Existing electronic-product-radiation authority has not been used to create modern chronic-exposure habitat standards.	Direct HHS/FDA to create performance standards and exposure-minimization procedures for protected indoor environments.
Federal procurement and building codes	No default requirement to prefer wired or optical systems in long-dwell public interiors, and no mandate to pair optical networking with circadian and low-TLM performance rules.	Require a wired / optical-first technology hierarchy, protected-room light schedules, and measured field and light budgets in federally supported protected occupancies.

5. Research agenda: how to find the true boundary conditions

The point of this paper is to define what can be codified now and what must be discovered next. The biggest mistake would be to write a law that speaks with false precision. The second biggest mistake would be to wait for perfect precision before protecting obvious long-dwell habitats.

5.1 Priority scientific questions

- Which features of indoor exposure matter most biologically: average field strength, harmonics, pulse repetition, duty cycle, burstiness, nighttime burden, or multi-source combinations?
- What minimum chronic magnetic-field levels in protected interiors are achievable in real buildings, and how much source reduction is possible through wiring design, panel placement, transformer isolation, and equipment procurement?
- Which parts of the 300 Hz-1 MHz region are most contaminated by modern power electronics, induction devices, wireless charging, and EV infrastructure inside buildings?
- How should low-frequency envelope content of RF systems be measured in a way that is reproducible, auditable, and relevant to actual room occupancy rather than only to device certification?
- How can light-communications systems be optimized to preserve network performance while minimizing temporal-light-modulation burdens and, for visible systems, keeping daytime, evening, and overnight melanopic exposure within optical-habitat targets?
- Which optical metrics best predict biological acceptability for integrated lighting-and-networking systems: vertical melanopic EDI, spectral composition, temporal-light-modulation metrics, eyelid illuminance during sleep, or combined indices?

5.2 Developmental and multi-generational priorities

If the long-term concern is biological fidelity rather than immediate irritation, then developmental timing becomes central. The literature already contains one-generation developmental signals - for example Aldad et al. (2012) reported hyperactivity and impaired memory in mice exposed in utero to cellular telephone radiation, and later systematic reviews on in utero exposure have treated prenatal and developmental endpoints as a priority topic. But true transgenerational evidence remains far thinner than advocacy language often suggests.

That is exactly why the federal program should require F0-to-F3 study designs wherever feasible, separate maternal from paternal exposure windows, and distinguish clearly between direct in utero effects, intergenerational effects, and true transgenerational inheritance. It should also prioritize co-exposure designs that combine power-frequency magnetic fields, switching-noise environments, and realistic wireless traffic instead of testing each source in isolation.

5.3 Measurement before litigation, measurement before ideology

To settle this domain, the United States needs rooms, not slogans. That means open datasets of field measurements from bedrooms, nurseries, classrooms, hospital bays, offices, and public housing; standardized logs of duty cycle and burst structure; and public procurement databases showing what happened when wired, optical, or low-ripple DC retrofits were installed.

In other words, a Biological Fidelity Act should fund a national electromagnetic habitat survey in the same spirit that air, water, and noise pollution became governable only after they became measurable at the scale of ordinary life.

6. Bottom line

The best current reading of the evidence does not support the claim that humanity has already identified one final forbidden wireless carrier frequency. It does support a quieter and more consequential conclusion: the time-varying low-frequency structure of indoor electromagnetic environments, and the timing and modulation structure of indoor optical environments, deserve to be treated as protected habitat.

If law follows that conclusion, the first protected domain is not 'all RF' and it is not 'nothing at all.' It is the indoor temporal habitat from 0 hertz upward through the low-frequency and intermediate-frequency bands that shape magnetic fields, harmonics, converter noise, induction systems, and the envelope structure of wireless exposure. That is where present evidence is strongest, where present regulation is least adequate, and where the easiest substitution pathways already exist.

This paper therefore recommends four immediate moves: protect long-dwell interiors first; write the statute around temporal structure, harmonics, and occupancy rather than carrier alone; add an optical-habitat code built around proper light at the proper time and low temporal-light-modulation burden; and build the transition around fiber, wired distribution, circadian-sane low-flicker optical networking, and carefully measured low-ripple DC pilots. That is the clearest available path toward a legally recognizable biofidelity zone while the science continues to refine the final thresholds.

Selected references underpinning this framework

World Health Organization. Radiation and health: non-ionizing exposure - ELF fields fact sheet. Reports average residential power-frequency magnetic fields of about 0.07 microtesla in Europe and 0.11 microtesla in North America, and summarizes the IARC classification of ELF magnetic fields as possibly carcinogenic to humans on the basis of childhood leukemia evidence.

Brabant C, et al. Exposure to magnetic fields and childhood leukemia: a systematic review and meta-analysis of case-control and cohort studies. Rev Environ Health. 2022;38(2):229-253. Concluded that ELF magnetic fields above 0.4 microtesla may increase childhood leukemia risk.

Amoon ATA, et al. Pooled analysis of recent studies of magnetic fields and childhood leukemia. Environ Res. 2021;204(Pt A):111993. Found the excess risk had declined to no association in recent pooled studies, while noting methodological explanations or a true disappearing effect were possible.

International Commission on Non-Ionizing Radiation Protection (ICNIRP). Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz-100 kHz). Health Phys. 2010. Public magnetic-flux-density reference level at 25-400 Hz: 200 microtesla.

Bodewein L, et al. Systematic review on the biological effects of electric, magnetic and electromagnetic fields in the intermediate frequency range (300 Hz to 1 MHz). Environ Res. 2019;171:247-259.

Lee HJ, et al. Effects of intermediate frequency electromagnetic fields. Arch Pharm Res. 2023. Review concluding that IF-EMF research remains limited, with some reported developmental or prolonged-exposure effects.

Karipidis K, et al. The effect of exposure to radiofrequency fields on cancer risk in the general and working population: A systematic review of human observational studies - Part I: Most researched outcomes. Environ Int. 2024;190:108983.

Cox, Calderon, Richmond et al. The effect of exposure to radiofrequency fields on cancer risk in the general and working population - Part II: Less researched outcomes. Environ Int. 2025;193:109121.

Sanagou M, et al. The effects of radiofrequency exposure on cognition: A systematic review and meta-analysis of human observational studies. Environ Int. 2024;186:108779.

Richmond C, et al. The effects of radiofrequency exposure on male fertility: A systematic review of human observational studies with dose-response meta-analysis. Environ Int. 2024;187:108817.

Mevissen M, et al. Effects of radiofrequency electromagnetic field (RF-EMF) exposure on cancer in experimental animals: A systematic review. Environ Int. 2025;193:109109.

Cordelli E, et al. Effects of RF-EMF exposure on pregnancy and birth outcomes: A systematic review of experimental studies on non-human mammals. Environ Int. 2025;196:109273.

Cordelli E, et al. Effects of RF-EMF exposure on male fertility: A systematic review of experimental studies on non-human mammals and human sperm in vitro. Environ Int. 2024;185:108509.

Meyer F, et al. The effects of radiofrequency electromagnetic field exposure on biomarkers of oxidative stress in vivo and in vitro: A systematic review of experimental studies. Environ Int. 2024;190:108904.

Juutilainen J, Hoyto A, Kumlin T, Naarala J. Review of possible modulation-dependent biological effects of radiofrequency fields. Bioelectromagnetics. 2011;32(7):511-534.

Panagopoulos DJ, Yakymenko I, De Iuliis GN, Chrousos GP. A comprehensive mechanism of biological and health effects of anthropogenic extremely low frequency and wireless communication electromagnetic fields. Front Public Health. 2025;13:1585441.

Petri AK, et al. Biological effects of exposure to static electric fields in humans and vertebrates: a systematic review. Environ Health. 2017;16:41.

Schmiedchen K, et al. Biological and health-related effects of weak static magnetic fields (<= 1 mT) in humans and vertebrates: A systematic review. Environ Res. 2020;186:109545.

Gerber DL, et al. Energy and Power Quality Measurement for Electrical Distribution in AC and DC Microgrid Buildings. Lawrence Berkeley National Laboratory accepted manuscript, 2021. Notes that DC buildings can reduce conversion losses and are usually devoid of 60 Hz harmonics, while also emphasizing the importance of converter architecture and power quality.

IEEE Std 802.11bb-2023. Light Communications amendment for IEEE 802.11 wireless LAN systems.

CIE S 026:2018. CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light. Defines alpha-opic quantities and melanopic equivalent daylight illuminance for characterizing visible-light exposure at the eye.

CIE Position Statement on Integrative Lighting - Recommending Proper Light at the Proper Time, 3rd edition, 2024. Summarizes current guidance toward high daytime melanopic exposure, much lower evening exposure, and near-darkness during sleep, while emphasizing that timing, spectrum, and intensity all matter and that correlated colour temperature alone can be misleading.

IEEE Std 1789-2015. Recommended practices for modulating current in high-brightness LEDs for mitigating health risks to viewers.

U.S. Department of Energy. Flicker Research. Summarizes temporal-light-modulation science, response metrics for direct flicker, stroboscopic and phantom-array effects, and the value of high-frequency or non-PWM driver strategies.

IEC 62471:2006 / CIE S 009:2002. Photobiological safety of lamps and lamp systems. Provides exposure limits, measurement methods, and classification for optical radiation hazards from electrically powered incoherent broadband sources.

47 U.S.C. 332(c)(7)(B)(iv) and FCC fact sheet on Section 704 of the Telecommunications Act of 1996. Preempts state and local regulation of wireless facilities on the basis of RF environmental effects when FCC rules are met.

Environmental Health Trust v. FCC, 9 F.4th 893 (D.C. Cir. 2021). Held that the FCC had not adequately explained its treatment of non-cancer effects, children, long-term exposure, pulsation or modulation, and environmental harms.

21 U.S.C. 360ii. Directs the Secretary to establish and carry out an electronic product radiation control program, develop performance standards, study exposure conditions to electronic product radiation and intense magnetic fields, and evaluate procedures for minimizing exposure.