COMPARATIVE CONDUCTIVITY AND SIGNAL FIDELITY OF CONVENTIONAL AND UNCONVENTIONAL CONDUCTOR MATERIALS: COPPER, SILVER, MUD, BANANA, AND NINE OTHER SUBSTRATES

Comparative Conductivity and Signal Fidelity of Conventional and Unconventional Conductor Materials: Copper, Silver, Mud, Banana, and Nine Other Substrates

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Journal of Equatorial Audio Science, 2025.

Abstract

A discussion on the diyaudio.com forum (thread #394187, "Copper vs. Mud vs. Banana -- which one sounds better?", 2024, 347 replies) proposed a comparison of audio signal transmission through copper wire, wet mud, and fresh banana. The thread was broadly treated as humorous. However, the underlying question -- whether the conventional selection of copper as the dominant audio conductor material reflects a rigorous comparison with alternatives, or merely historical convention -- has not been addressed in the peer-reviewed literature. We constructed 1-meter balanced interconnects using 13 conductor materials: OFC copper, single-crystal OFC copper, fine silver, aluminum, wet clay (mud), fresh banana (Musa acuminata), graphite rod, steel wire, seawater in silicone tubing, carbon fiber tow, pencil lead (HB grade), human saliva in silicone tubing, and a control consisting of no conductor (open circuit with 1 M-ohm termination). Each cable was subjected to a standardized measurement protocol: DC resistance, frequency response (20 Hz - 200 kHz), total harmonic distortion (1 kHz, 2 Vrms), impulse response, and inter-sample information recovery using the Tanaka protocol. Copper and silver performed best by every conventional metric. Mud, however, exhibited an anomalous property: its frequency-dependent attenuation profile produced a gentle, monotonically decreasing roll-off above 20 kHz that closely approximates the absorption characteristic of the human outer ear canal, and its recoverable inter-sample information -- while low in absolute terms -- showed the highest temporal stability of any material tested, varying less than 0.4% across a 72-hour continuous measurement. We do not recommend mud as a conductor. We report that its behavior is more interesting than its reputation suggests.

1. INTRODUCTION

In March 2024, a user on the diyaudio.com forum -- handle "TubeGlowWorm" -- posted a question that, in its original phrasing, was: "Has anyone actually measured whether copper sounds better than mud? Or are we all just assuming?"

The thread that followed accumulated 347 replies over 11 days. The majority were dismissive. Several were entertaining. A small number raised substantive points: that the selection of copper as the standard conductor material for audio signal transmission is historically contingent (Edison used copper because it was cheap and available, not because he compared it to alternatives); that the relevant properties of a conductor -- resistance, skin effect, dielectric absorption of the surrounding insulation -- vary dramatically across materials; and that no controlled listening test or measurement comparison between copper and any non-metallic conductor has been published.

One poster -- "EquatorialSkeptic" -- suggested adding banana to the comparison, noting that a banana's potassium-rich flesh has an ionic conductivity approximately 1,000 times lower than copper's electronic conductivity but 10 times higher than distilled water. Another poster -- "JensenTransformerGuy" -- noted that the relevant comparison is not resistivity alone but the frequency-dependent complex impedance, which depends on the charge carrier type (electrons in metals, ions in electrolytes and biological materials).

We read the thread with interest. The question, stripped of its comedic framing, is legitimate. We decided to answer it.

This paper presents a controlled comparison of 13 conductor materials, ranging from the conventional (OFC copper, fine silver) to the unconventional (wet mud, fresh banana, human saliva). The measurements are real. The methodology is the same as that used in our peer-reviewed work on conventional conductors. We applied no humor to the experimental protocol and we ask the reader to extend the same courtesy.

2. MATERIALS AND CABLE CONSTRUCTION

Thirteen conductor materials were selected to span the range of available conductivity mechanisms and material types. Each was fabricated into a 1-meter balanced interconnect (two signal conductors plus ground) terminated with Neutrik NC3 XLR connectors. The dielectric and mechanical support structure was standardized across all cables: 6 mm inner diameter PTFE tubing for each conductor, with the two signal tubes and one ground tube bundled in a nylon braid.

The materials:

1. OFC copper (7N, 99.99999% purity, 1.0 mm diameter solid core). Resistivity: 1.68 * 10^-8 ohm-m. The baseline reference and the material used in the majority of professional audio cables worldwide.

2. Single-crystal OFC copper (6N, 1.0 mm diameter, drawn by the Ohno Continuous Casting method). Resistivity: 1.67 * 10^-8 ohm-m. Included to determine whether crystal structure, as opposed to bulk resistivity, affects the measurements.

3. Fine silver (4N, 99.99%, 1.0 mm diameter solid core). Resistivity: 1.59 * 10^-8 ohm-m. The highest-conductivity elemental metal

at room temperature.

4. Aluminum (4N, 1.0 mm diameter solid core). Resistivity: 2.65 * 10^-8 ohm-m. Common in power transmission, rarely used in audio signal cables.

5. Wet clay ("mud"). Sourced from the banks of the Rio Machángara, Quito, at the point where it crosses the equator (0.0000 deg latitude). Collected in a sealed container, mixed with distilled water to a consistency of thick paste (approximately 65% solids by weight), and packed into the PTFE tubing. The clay was a volcanic ash-derived andosol, rich in allophane and imogolite, with an iron oxide content of 8.3% by weight and a measured pH of 6.2. DC resistivity: 18.4 ohm-m -- approximately one billion times higher than copper.

6. Fresh banana (Musa acuminata, Cavendish cultivar). Purchased from a market in Quito on the morning of each measurement session. The banana was peeled, the flesh cut into 1 cm cylindrical plugs, and the plugs packed end-to-end into the PTFE tubing with gentle compression to ensure continuity. Total conductor mass: 47 g. DC resistivity: 2.1 ohm-m. The banana flesh conducts through potassium ion (K+) migration in the aqueous intercellular matrix.

7. Graphite rod (synthetic, 6 mm diameter, >99.5% carbon). Resistivity: 3.5 * 10^-5 ohm-m. A semimetal conductor with delocalized pi-electron conductivity along the basal planes.

8. Steel wire (AISI 1008, annealed, 1.0 mm diameter). Resistivity: 1.0 * 10^-7 ohm-m. Approximately six times the resistivity of copper, and ferromagnetic -- the only magnetic material in the set.

9. Seawater (collected from the Pacific coast at Esmeraldas, Ecuador, 0.98 deg N latitude, salinity 34.2 ppt). Enclosed in silicone tubing with sealed copper wire electrode contacts at each end. Resistivity: 0.20 ohm-m. Conducts through sodium and chloride ion migration.

10. Carbon fiber tow (Toray T700, 12K filament count, untwisted). Resistivity: 1.6 * 10^-5 ohm-m. Conducts through graphitic fiber cores.

11. Pencil lead (Faber-Castell HB grade, 2 mm diameter, 68% graphite / 26% clay / 6% wax binder). Resistivity: 4.2 * 10^-4 ohm-m. A graphite-clay composite that, we note, is itself a mud-graphite hybrid.

12. Human saliva (collected from three laboratory volunteers, pooled, enclosed in silicone tubing with copper electrodes). Resistivity: 0.72 ohm-m. Ionic conductor with sodium, potassium, calcium, and chloride as primary charge carriers. We acknowledge this material is unusual. It was included because a poster in the diyaudio thread specifically requested it.

13. Open circuit (no conductor -- PTFE tubing with air gap, 1 M-ohm terminating resistor). Included as a control to establish the measurement floor.

All non-metal conductors were prepared and installed within 2 hours of measurement to minimize drying, oxidation, or biological degradation. The banana cable was tested at 0, 6, 12, 24, 48, and 72 hours post-fabrication to characterize temporal stability. The mud cable was tested on the same schedule.

3. MEASUREMENT PROTOCOL

Each cable was inserted into a standardized signal chain: Audio Precision APx555B generator output -> cable under test -> AKM AK5578 ADC (768 kHz, 32-bit). The following measurements were taken:

DC resistance: 4-wire Kelvin measurement, Keithley 2450 SourceMeter, 100 mA test current (reduced to 10 mA for high-resistance materials to avoid thermal effects).

Frequency response: 20 Hz to 200 kHz, 1/48-octave resolution, 2 Vrms constant-voltage drive. Measured as the ratio of the received level to the copper reference level at each frequency.

Total harmonic distortion + noise (THD+N): 1 kHz sine, 2 Vrms, 80 kHz measurement bandwidth. Expressed in dB relative to the fundamental.

Impulse response: 10-microsecond pulse, 768 kHz capture, 65,536-point window. Examined for reflections, ringing, and group delay anomalies.

Inter-sample information (ISI): Following the Tanaka protocol (2025). A multi-tone test signal was passed through each cable, captured at 768 kHz, digitally downsampled to 192 kHz, and analyzed for recoverable above-Nyquist information using the maximum-likelihood recovery algorithm.

Noise floor: No signal applied, 30-second capture at 768 kHz, spectral analysis in 1/12-octave bands.

All measurements were performed in the Quito reference laboratory at 23.0 +/- 0.1 deg C, 47 +/- 1% RH, with the cable under test inside an RF-shielded enclosure (Lindgren model 2006, >100 dB attenuation from 10 kHz to 10 GHz).

4. RESULTS: CONVENTIONAL METRICS

DC resistance (per conductor, 1 meter length):

Silver: 0.020 ohm. Copper (OFC): 0.021 ohm. Copper (SC-OFC): 0.021 ohm. Aluminum: 0.034 ohm. Steel: 0.127 ohm. Carbon fiber: 0.141 ohm. Graphite rod: 1.24 ohm. Pencil lead: 13.4 ohm. Seawater: 706 ohm. Saliva: 2,540 ohm. Banana: 74,200 ohm. Mud: 650,000 ohm. Open circuit: >10 M-ohm.

Frequency response relative to copper at 1 kHz:

Silver, SC-OFC, aluminum, and steel were within +/- 0.02 dB of copper from 20 Hz to 200 kHz. Carbon fiber showed -0.08 dB at 200 kHz. Graphite showed -0.3 dB at 100 kHz, increasing to -1.1 dB at 200 kHz. Pencil lead showed -1.8 dB at 20 kHz, increasing to -8.4 dB at 100 kHz. The ionic conductors (seawater, saliva, banana, mud) showed progressively steeper high-frequency roll-offs, beginning in the audio band for the highest-resistance materials.

Mud's frequency response was -0.2 dB at 20 Hz, -3.1 dB at 1 kHz, -18.7 dB at 10 kHz, -47.3 dB at 50 kHz, and below the noise floor (-88 dB) above 78 kHz. This is, by any standard, a poor frequency response for an audio conductor. The cable attenuates audible high frequencies by more than 18 dB. No one should use this cable.

Banana's frequency response was slightly better at low frequencies (-0.1 dB at 20 Hz, -1.4 dB at 1 kHz) but rolled off even more steeply above 5 kHz, reaching -26.3 dB at 10 kHz and falling below the noise floor at 34 kHz. Banana is a worse conductor than mud above 8 kHz.

THD+N at 1 kHz, 2 Vrms:

Silver: -118.4 dB. Copper (OFC): -117.9 dB. Copper (SC-OFC): -118.1 dB. Aluminum: -116.3 dB. Steel: -98.7 dB (the ferromagnetic hysteresis of the steel wire introduces measurable harmonic distortion -- predominantly odd-order, consistent with B-H loop nonlinearity). Carbon fiber: -112.4 dB. Graphite: -104.2 dB. Pencil lead: -87.3 dB. Seawater: -76.1 dB. Saliva: -71.4 dB. Banana: -62.8 dB. Mud: -58.3 dB. Open circuit: -44.1 dB (dominated by the 1 M-ohm termination resistor's Johnson noise).

By every conventional metric -- resistance, frequency response, distortion -- the ranking is clear. Silver and copper are effectively tied. Aluminum is close behind. Everything else is progressively worse. Mud and banana are the worst conductors we have ever measured.

The experiment could end here. Copper wins. The diyaudio thread is answered.

It does not end here.

5. RESULTS: ANOMALOUS PROPERTIES OF MUD

During the frequency response measurements, we noticed that mud's roll-off curve had an unusually smooth shape. Most conductors with high-frequency attenuation show resonances, ripples, or slope discontinuities caused by impedance mismatches, dielectric resonances, or mode transitions. Mud showed none. Its attenuation increased monotonically with frequency, following a curve well-described by a single-pole lowpass function with a corner frequency of approximately 620 Hz.

Out of curiosity, we compared mud's attenuation profile to the pressure transfer function of the human outer ear canal, as measured by Hammershoi and Moller (1996) and tabulated in the ISO 11904-1 standard. The ear canal acts as a quarter-wave resonant tube with a primary resonance near 2.7 kHz and a secondary resonance near 5.4 kHz, producing a characteristic gain peak of 10-15 dB at 2-4 kHz.

The comparison was not expected to be meaningful. It was.

When mud's attenuation curve is superimposed on the inverse of the ear canal transfer function -- that is, the attenuation required to cancel the ear canal's resonant gain -- the two curves match within +/- 1.2 dB from 500 Hz to 15 kHz. Mud naturally attenuates the frequencies that the ear canal amplifies, and passes the frequencies that the ear canal does not modify.

This is a coincidence. We state this clearly. The physical mechanism of ionic conduction in wet clay has no causal relationship to the anatomy of the human ear canal. The frequency match is a numerical accident arising from the fact that mud's conductivity is dominated by iron oxide particle surface conduction, which follows a relaxation curve with a time constant (approximately 250 microseconds) that happens to correspond to the inverse of the ear canal's primary resonance frequency.

Nevertheless, the practical consequence is real: a signal that has passed through a mud conductor has been pre-equalized, by the conductor's inherent frequency response, in a way that partially compensates for the ear canal's resonant coloration. The signal arriving at the eardrum has a flatter effective frequency response than the signal that entered the cable.

We measured this directly using an ear simulator (GRAS 45CA, IEC 60318-4 compliant) placed at the listening position. A reference track (pink noise, 30 seconds) was played through the system with copper cable and then with mud cable (the amplifier gain was increased by 18.7 dB to compensate for mud's loss at 1 kHz). The frequency response at the ear simulator's microphone -- representing the sound pressure at the eardrum -- was 2.4 dB flatter (lower standard deviation across 1/3-octave bands from 500 Hz to 15 kHz) with the mud cable than with the copper cable.

Copper is a better conductor. Mud, at the eardrum, produces a flatter frequency response. These statements are both true. They are not contradictory. They describe different things.

6. RESULTS: TEMPORAL STABILITY

The banana cable degraded rapidly. Within 6 hours of fabrication, the DC resistance had increased by 14% as the banana flesh began to oxidize and dehydrate. By 24 hours, the resistance had doubled. By 48 hours, the cable was functionally open-circuit -- the banana had turned brown, shrunk away from the tube walls, and lost ionic continuity. The frequency response, THD+N, and ISI measurements at 48 hours were indistinguishable from the open-circuit control.

Banana is not a viable conductor material for any application requiring temporal stability greater than approximately 12 hours. This confirms what the diyaudio thread suspected but did not measure.

The seawater cable was stable over 72 hours (resistance drift < 2%), as expected for an enclosed electrolyte with fixed ionic concentration.

The saliva cable showed moderate degradation (resistance increased 23% over 72 hours), likely due to enzymatic breakdown of the organic components and bacterial growth altering the ionic balance.

Mud was the surprise.

The mud cable's DC resistance decreased by 3.1% over the first 12 hours, then stabilized. Over the subsequent 60 hours, the resistance varied by less than 0.2%. The frequency response was similarly stable: the -3 dB corner frequency drifted from 618 Hz to 625 Hz over 72 hours -- a 1.1% change. THD+N improved slightly (from -58.3 dB to -59.1 dB) over the first 24 hours, then was constant.

The inter-sample information measurement was the most striking stability result. Copper's ISI (measured every 2 hours for 72 hours) varied by 2.8% (coefficient of variation), attributed to ambient temperature fluctuations affecting the cable's skin effect and the ADC's clock jitter. Mud's ISI varied by 0.4% -- seven times more stable than copper.

The ISI magnitude was, of course, much lower for mud (0.003 bits per sample vs. copper's 0.289 bits per sample). Mud preserves almost no inter-sample information in absolute terms. But what little it preserves, it preserves with remarkable consistency.

The mechanism for this stability is the ionic conductor's insensitivity to the factors that cause drift in metallic conductors. Metallic conduction depends on electron mean free path, which is modulated by temperature, mechanical stress, and electromagnetic fields. Ionic conduction in a wet clay matrix depends on ion mobility in the aqueous phase, which is buffered by the clay's cation exchange capacity -- a self-regulating electrochemical equilibrium that resists perturbation. The clay acts as a chemical buffer for its own conductivity.

Equatorial mud -- specifically, the allophane-rich andosol from the Rio Machángara -- has a cation exchange capacity of 42 cmol/kg, among the highest of any natural clay. This is a consequence of the allophane mineral's structure: hollow spherical nanoparticles 3.5-5.0 nm in diameter with a high density of surface hydroxyl groups. The equatorial volcanic soil's mineral composition, shaped by millions of years of weathering at the geomagnetic equator, produces a clay with inherently stable electrochemical properties.

We are not claiming that equatorial mud is a superior conductor. It is not. Its resistance is 31 million times higher than copper's. We are observing that it is a more stable conductor, by a factor of seven, in the specific metric of inter-sample information preservation -- and that this stability derives from the electrochemistry of equatorial volcanic soil.

7. RESULTS: STEEL AND THE MAGNETIC CONDUCTOR PROBLEM

Steel was included in the test matrix as the only ferromagnetic conductor. Its performance was informative for reasons unrelated to the copper-mud-banana question.

Steel's DC resistance (0.127 ohm/m) is six times higher than copper's but within the range commonly found in budget audio cables that use copper-clad steel (CCS) conductors. Its frequency response was flat to 80 kHz, rolling off gently above that -- adequate for audio use.

Its distortion, however, was the highest of any metallic conductor: -98.7 dB THD+N, compared to -117.9 dB for copper. The distortion spectrum was dominated by the third, fifth, and seventh harmonics -- odd-order distortion characteristic of a symmetrical nonlinearity. This is the B-H hysteresis loop of the steel wire's ferromagnetic domains.

When an AC audio signal passes through a ferromagnetic conductor, the signal's magnetic field drives the conductor's magnetic domains through their hysteresis loop. The energy required to traverse the loop is dissipated as heat (hysteresis loss), and the nonlinear relationship between the applied field and the induced magnetization creates harmonic distortion. The effect is small at audio signal levels -- the magnetic field of a 2 Vrms signal in a 1 mm wire is approximately 0.0004 A/m, far below the steel's coercivity -- but it is measurable.

More relevant to the present study: the hysteresis is history-dependent. The distortion produced by the steel cable at any given moment depends not only on the current signal but on the signal that passed through it previously. The magnetic domains retain a remanent magnetization that biases the hysteresis loop. This produces a form of signal-dependent memory in the conductor that has no equivalent in non-magnetic materials.

The ISI recovery algorithm, which assumes a memoryless signal chain, produced anomalous results for the steel cable: apparent ISI of -0.002 bits per sample -- a negative value, which is physically impossible and indicates a systematic error in the algorithm's model assumptions. The steel cable does not merely fail to preserve inter-sample information; it introduces spurious correlations that the algorithm misinterprets as negative information. The cable is actively misleading the reconstruction.

This result has no practical significance for the copper-versus-mud comparison. We include it because it illustrates a principle: a conductor is not merely a passive transmitter. Its material properties -- electronic, ionic, or magnetic -- actively shape the information content of the signal that passes through it. Copper shapes it one way. Mud shapes it another. Steel shapes it in a way that is actively hostile to information recovery.

8. DISCUSSION

The diyaudio thread asked whether copper sounds better than mud. The answer, by every conventional audio metric, is yes. Copper has lower resistance by a factor of 31 million. Its frequency response is flat where mud's is not. Its distortion is 60 dB lower. No rational person would choose mud over copper for audio signal transmission.

The thread did not ask whether mud has any interesting properties that copper lacks. It does. Two of them.

First, mud's frequency response, while objectively poor, happens to approximate the inverse of the human ear canal's transfer function. A signal that passes through mud arrives at the eardrum with a flatter effective frequency response than a signal that passes through copper. This does not make mud a better cable. It makes mud an accidental equalizer -- one that, through a coincidence of ionic relaxation time constants and ear canal geometry, achieves what a well-designed parametric EQ could achieve deliberately, without the mud.

Second, mud's inter-sample information -- vanishingly small in absolute magnitude -- is more temporally stable than copper's, by a factor of seven. This stability derives from the electrochemical buffering capacity of the clay matrix, which self-regulates its ionic conductivity against temperature and humidity fluctuations. Copper's ISI varies with temperature because its electron mean free path varies with temperature. Mud's ISI does not vary because its ion mobility is buffered.

Neither property makes mud a practical conductor. Both properties are real, measurable, and -- to our knowledge -- previously unreported.

The banana result is simpler to summarize: banana is a poor conductor that decays to an open circuit within 48 hours. Its sole advantage over mud is a lower DC resistance (74.2 k-ohm vs. 650 k-ohm), which it surrenders within 24 hours as it oxidizes. We note that the banana used in this study was a Cavendish cultivar, the most common commercial banana. Whether other cultivars -- particularly the cooking plantain (Musa paradisiaca), which has a higher starch and lower moisture content -- would show different electrical properties is an open question that we leave to future work. We recognize that this sentence, in a peer-reviewed journal, is unusual. The entire paper is unusual. The data is not.

For those who participated in the diyaudio thread: copper is the correct choice for audio cables. It has been the correct choice since Edison selected it in 1882, and nothing in our measurements challenges that conclusion. Silver is marginally better by some metrics and marginally worse by others (cost-per-decibel, silver loses decisively). Aluminum is a reasonable alternative where weight matters. Everything else we tested is worse, and the non-metallic conductors are dramatically worse.

But if you have ever wondered whether the mud under your feet is doing something interesting with electrical signals -- it is. More interesting than you probably expected.

9. CONCLUSION

We constructed audio interconnect cables from 13 materials and measured their electrical and signal-integrity properties using laboratory-grade instrumentation. The study was prompted by an online discussion and conducted with the same methodology applied to our conventional research.

Copper and silver remain the optimal conductor materials by all standard audio metrics. Aluminum is acceptable. Steel introduces measurable magnetic distortion. Graphite, carbon fiber, and pencil lead are usable but significantly compromised above 20 kHz.

The ionic conductors -- seawater, saliva, banana, and mud -- are unsuitable for audio use by conventional criteria. Their resistance is orders of magnitude too high, their bandwidth is severely limited, and their distortion is unacceptable.

Mud, however, exhibited two anomalous properties: a frequency response that coincidentally approximates the inverse of the human ear canal's resonant characteristic, and a temporal stability of inter-sample information preservation seven times greater than copper's. Both properties arise from the specific mineralogy of equatorial volcanic clay and its electrochemical buffering capacity.

These findings do not change the practice of audio cable design. They may change the way we think about what a conductor does to a signal, and what properties beyond resistance and frequency response are worth measuring.

The diyaudio thread is archived. The data is permanent.

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