THE FOURTH DEE: TURNING OVER A NEW LEIF

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At the time Niku Yeng received an official offer of employment from Analog Devices in 2025, shortly after her interview with Dr. Leif, she had briefly considered two others. All held the prospect of an exciting and rewarding career in advanced microelectronics. But she recalled that the interviewer at one of the companies seemed to be unusually concerned about her willingness to accept highly detailed directives and to rapidly produce solutions in response to specific market demands. She'd been trained to expect this, in an industry that had become just another provider of commodity items—much like hyperphase foods or disposable clothing—she nonetheless felt that a strong emphasis on products focused only on near-term needs was myopic, and it was bound to discourage originality and clash with any aberrant, singular vision, leading to mediocrity and a poor reputation for quality and service.

The third offer was quite different. During that interview, all the questions were concerned with very tentative technologies, facets of the ongoing struggle to make nanostructures not only as crude logical elements but in the vastly more complex arena of analog design—where device quality is of paramount importance. Very good progress had been made in applying hybrid neural networks (such as those in the greeter at Galaxybux) having quasi-analog circuits on silicon substrata acting as message concentrators for the layers of super-stressed fibers of dimethyl-3, 5-ribocarbon—which provide the fast-learning, slow-fading memory cells with massive parallelism for noise immunity and redundancy. But the broad promises of the nanodisciplines, peaking just after the turn of the century, had all but evaporated between 2012 and 2018, as more pragmatic concerns dictated which technologies could deal with the peculiar demands of analog signals. Furthermore, with atmospheric CO_2 rising at an imminently perilous rate, research in global climate control now held center stage in every country. Degree courses in this field had become the first choice of many a young scientist who aspired to a place in history.

But, more than any other factor, it was the sheer enthusiasm of Leif, his keen interest in exploring some still-unanswered, though seemingly rudimentary, questions about analog circuits that led Niku to accept ADI's offer for a position as *Entry-Level Product Originator*. At first, she was upset to discover that her work would not be under Leif—who was, it seemed, a sort of roving consultant to various groups in the company. (She later discovered that he got involved in entry interviews only in cases where exceptional talent was evidenced during prescreening, a revelation that had helped to assuage her initial disappointment.)

By now, though, she felt sure she'd made the right decision. Leif was no mystical hermit. He regularly wandered around the local design groups, asking penetrating questions about their projects, vigorously engaging in theoretical issues here or offering advice there, and applying a deft technique of asking leading questions that left no one feeling put down. It was on one of these routine visits, roughly two months after Niku had joined her team, that he sat down with her for a while. Before long, she was reminding Leif that he had never gotten around to telling her what the "Fourth Dee" of analog design was all about.

"Ah, yes, those 'Dees.' What do you remember about them?" he quizzed.

"Well, you told me that analog products are far more **Durable** than digital, often having generations measured in decades; and that the little circuits that go into them are highly **Diverse**—like the myriad musical tunes composed out of just a few notes; and that their constituent components, as well as the actual signals, have a crucial **Dimensional** aspect."

"Hearing you summarize them so well, Niku, they don't appear to be especially profound, do they? Are you finding these issues to be as important as I have suggested?"

"Not really. I believe you, of course. But any truths of substance have to be learned, from one's individually acquired knowledge and hands-on experience, rather than accepted simply on their face value," Niku said, sounding wiser than her years. "Are you going to tell me what the Fourth Dee is now?"

"Tell you what," said Leif mischievously. "I dropped by to see what you've been doing, and I'd first like to hear all about that. Perhaps the answer you're seeking will occur to you by the time you have finished telling me about your project."

Niku explained that she hadn't yet been assigned a development project. She'd been given time to familiarize herself with the lab environment, the many in-house and foundry IC processes that would be available to her, and the vast network of databases and design centers in every corner of the United World. She had also been familiarizing herself with the large suite of simulation tools called GE°E, pronounced "gee-oh," which she was told stood for *general electro*^{O}*ptical emulator*. She had never been exposed to anything so powerful and all-encompassing, let alone so user-friendly and fast.

"So how are you getting along with your teammates?"

"Oh, they're okay." She briefly hesitated—but then mentioned that several days ago she'd heard a noisy argument in the halls about exactly how high-frequency oscillators start up. She was quite surprised that this was a matter for disagreement.

"It appears that Bob somebody—he has a CyberCyte" (Leif's wry smile acknowledged his recognition of this character) "had stated in no uncertain way that oscillators start only because of a sudden step on the supply, or on a bias line. A couple of the guys seemed to agree with him, but most didn't. They argued that if a circuit satisfies the conditions required for sustained oscillations, it should only depend on its internal noise to start, and the longer it takes, the better. The argument got pretty fierce at times!

"So I decided that studying this question in depth would be an excellent learning experience, as my first serious exercise in the use of GE°E. But I have told no one about this, because it might seem a waste of the company's time."

"Absolutely not, my good young lady! If you ever start to believe that the exploration of such fundamental questions is a waste of time—even *after* you have product responsibilities—you'll hear from me! Do you know what *genius* is?"

Niku blinked, startled by Leif's sudden intensity.

"Genius is nothing more than this: The curiosity of childhood constantly recaptured—every day of your life! It wouldn't be proper for me to advise you to allow your curiosity to rule your actions when you become faced with urgent deadlines. But if those deadlines should ever become the constant feature of your life, you'll feel frustrated by the pressure, for perhaps a year or two, and later miserable and irritable. Eventually, your precious flame of individualism will be fully extinguished. Years ago, this would happen to a fine product designer, who would turn into a designing robot by the pressures of the work. Today, we have a better awareness of these dangers. In fact, it is my job to ensure that creativity flourishes in this group, by defending flights of the imagination—such as the one you are starting to tell me about!"

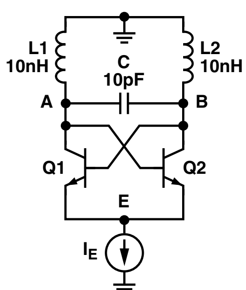
"Okay, but I'm no genius! Just very curious, simple-minded, and terribly inexperienced," she said, blushing deeply. "Well, to start with, it seemed obvious that if an oscillator actually did start up through being disturbed by a supply transient, it would be a pretty poor circuit!"

"How does that follow?" said Leif, knowing full well where this was going.

"Well, the guys in the hall were talking about RF oscillators, for which phase noise is a critical performance issue; and if such an oscillator is easily upset by supply noise—enough to induce it to start up from cold—then I reasoned it would not be in the league they were talking about. It was only a short step to conclude that oscillators for demanding applications, as in this TransInformer" —Niku put her PDA on the table— "must use a *fully balanced* cell topology, if for no other reason than to reject the common-mode noise voltages, but also to minimize the even harmonic terms."

"Splendid! These are quite remarkable leaps of the imagination! I'm beginning to think that the Fourth Dee may not be one you need to worry about! But—keep going!"

"Well, it just seems like common sense to me. Anyway, I wanted my test cell to be as simple as possible, to reduce the number of unknown influences, so I used this ..." Niku pulled up the circuit on the screen of her PDA (Figure 1). "I know it's not a practical oscillator. For example, I learned in one of my courses at Nova Terra that once it does start oscillating, the amplitude will build up until the transistors start to saturate, and then the frequency plunges. I was interested not only in whether it will start under disturbed conditions; I also wanted to verify that the circuit noise is important to startup, and to learn *exactly how* this process unfolds over time—the oscillator's start-up trajectory, I suppose you'd call it. And I wanted to discover the relationship between the tail current required to sustain oscillation and the size of its resistive load, and ..."



TO MINIMIZE THE INTRODUCTION OF DISTRACTING COMPLICATIONS OF THE KIND FREQUENTLY ENCOUNTERED IN PRACTICAL OSCILLATORS, Q1 AND Q2 ARE INITIALLY ALLOWED TO BE "IDEAL"; THAT IS, BF = BR = VAF = VAR = INF. AND THE DEVICE RESISTANCES AND CAPACITANCES ARE ZERO; τ_f = 10ps.

LIKEWISE, FOR THE INITIAL EXPERIMENTS, THE TANK IS ASSUMED TO BE LOSS-LESS AND WITHOUT A LOAD.

I_E IS TURNED ON VERY RAPIDLY, AND THE CONSEQUENCES ARE OBSERVED FOR A VARIETY OF CONDITIONS, WHICH WILL BE ELABORATED ON IN DETAIL DURING FURTHER DISCUSSIONS WITH DR. LEIF.

Figure 1. Niku's First Basic Experimental Oscillator. Note that the only "supply" is the current I_E, further minimizing sources of enigma.

"Niku! Whoa!" said Leif, again looking rather serious. "Are you aware that you have set forth a series of studies—solely for your own enlightenment and pleasure—on a complex topic that others have regarded as a sufficient basis for a thesis degree?"

"Oh, not really. I didn't expect these virtual experiments to take very long, using GE°E. As it turned out, these studies brought to my attention a long, connected sequence of questions, as I saw various effects coming into play—some quite puzzling at first—and I wanted to explain them all. I have written them up, in case anyone else might be interested," said Niku.

"I have no doubt of that! May I put your name into our schedule of Daedalus Days?"

"What's a 'Daedalus Day'?" she giggled.

"Oh, I don't want to break your train of thought right now, but we will certainly get back to that, sometime," said Leif.

"Okay. Let's see. Oh yes! I felt it would be a good idea to further minimize the unknowns by using *ideal* bipolar transistors. I knew that, as long as the fundamental shot noise was modeled—and of course the BJT's beautifully straightforward transconductance—then, including the realism of the complex full transistor model would add nothing to help me gain the insights I was looking for. So I set the junction resistances and capacitances to zero, and the forward and reverse betas, as well as the forward and reverse early voltages, to infinity. Everything else used default values; except that, even though I wasn't interested in exactly modeling the base charge terms, I included a τ_F of a few picoseconds."

"That leaves very little of the reality, Niku! Are you confident that these drastic simplifications can be justified?" asked Leif. But he was not frowning, only putting her to the test.

"Yes, I think so. Originally, these experiments were intended to demonstrate only that an exactly balanced, *noise-free* oscillator will not start up when the tail current switches on suddenly, even if its rise time is less than the tank period, and even without any load. I also had a hunch that it wouldn't start up if I introduced a deliberate imbalance, provided the rise rate of the tail current was below a critical value, which I wanted to quantify; and certainly not with a load resistance below a critical value across the tank. By the way, I could have used two equal and separate tanks as loads, but that would introduce one more capacitor and another degree of freedom in the behavior."

"Good thinking. So, how did you upset the perfect balance?" asked Dr. Leif.

"I just altered the relative size of one of the transistors, using the SIZE parameter," she explained. (Note: Although GE°E is a far cry from SPICE, a surprising number of its commands, variable names, and other parameters can be traced to that earlier era.) "And, Dr. Leif, I wanted to add that as these studies progressed, the circuit opened up its many secrets to me; and I was glad I'd chosen to use primitive models because, even with these, there were times when I had to think hard to explain what was going on. It's safer to add in the additional reality of the full transistor model in small steps. Then you can see precisely at what point some puzzling new phenomenon first appears."

"Yes, many of us appeal to that paradigm, particularly when we are exploring a novel cell topology. It was called 'Foundation Design,' about 50 years ago, by one of ADI's Fellows. Well, now that you have whetted my appetite, Niku, tell me: How did you start your journey, and what did you discover first?"

"The first thing I did was to demonstrate that the application of a 10-mA tail current, I_E, having a 1-ps rise time, would never start this perfectly balanced oscillator under any of the conditions I tested. Of course, such a shock probably *would* be the primary reason for startup in a real circuit, which is always unbalanced, to some degree. But bias currents don't appear this quickly!"

"Now, from what you are telling me, I gather you are running GE°E in its primitive mode, as a SPICE emulator; because none of today's circuit simulators will nicely leave such an oscillator circuit in its meta-stable condition. By the way—*why* is that?"

"Oh, I know what you're getting at! Yes, that's correct. I chose to run the initial simulations in the old SPICE mode because I wanted to temporarily eliminate real-world noise processes. The SPICE-based simulators of, say, 2005 could predict small-signal noise values quite well, provided the device models were correct. However, SPICE only 'knows about' noise in a numerical sense, and merely handles the math to add up all the numbers. It has no idea about noise as a *process in time*—it does not treat the noise mechanisms in the various elements as a set of *time-stochastic variables*, whereas GE°E does."

"Precisely! Good. I assume that you used tight convergence tolerances to ensure the simulator wasn't simply stuck inside a broad numerical tolerance range. And I guess you chose 10 mA simply as a representative tail current for this type of oscillator. Okay, so at this juncture, you felt justified that those 'start-by-spike' fellas were incorrect?"

"Oh, no; it was just the first step. I really wanted to demonstrate that, in practice, the noise voltages across the tank at resonance would be the more significant source of disturbance, and that in a real circuit, with or without mismatches, noise is the root cause of the start-up trajectory. In fact, during my CyberFind studies, I turned up an article in *Analog Dialogue* about this, going back to 2006. It was very helpful. But I had to find out for myself."

Leif smiled with a mixture of approval and growing affection for this unusually curious and perceptive young mind.

"My next step was to introduce a 20% mismatch, equivalent to about 5 mV of V_{BE} difference, by giving Q1 a SIZE factor of 1.2 and again pulsing the tail current. Clearly, if this current appears very rapidly, with a rise time similar to the oscillator's period, it is bound to generate a voltage change across the tank, and even the slightest disturbance will get things going. So, I thought it would be interesting to ask how large that voltage would be."

Her mentor struggled to be ready with a quick calculation, in case Niku asked, "Do you know what I found?" Alas, it wasn't immediately obvious to him how to figure it out. With his eyes loosely closed in concentration, he could have been asleep.

"Dr. Leif? I said, 'Do you know what I found?'"

"Well, let me see now," he replied, still not having the answer he had hoped would come to mind. "The amplitude of the initial step of differential voltage across the tank, labeled V_{OUT} in your sketch, must be proportional to the step in tail current, I_E, and to the 20% mismatch—which gives us a factor of 0.2 times I_E for the current step into the tank, which is 2 mA. But then, the load resistor complicates things ..."

"No, wait! The difference current is $[(1.2/2.2)I_E - (1/2.2)I_E]$, and that's only 0.909 mA," she corrected him. "And remember, these initial studies assumed an *open-circuit* tank. Also, my idealized circuit assumed no other losses in the tank inductors, the capacitor, or the transistors. But I reduced this to an even more basic question. Setting aside the active circuit, and the effect of its power gain, what happens if an almost instantaneous step of current is applied to an LC tank? What is the voltage waveform just after t-zero? And since there is no damping, that question is equivalent to asking: 'What is the amplitude of the undiminished ringing, a true oscillation at $1/2\pi\sqrt{(LC)}$ in the tank voltage?'"

The situation was suddenly reversed. Leif was likely to have said, "I dunno. What is it?" even if he *did* know; he understood that the art of teaching must necessarily involve a great deal of humility, and allow students to feel the full glow of their proud discoveries. But the fact was, today he didn't have a clue. He honestly replied, "Niku, you have a way of asking the darnedest questions! This one is simple, as are all the best questions; but it's not one I've thought about before. Classically, it would be solved by using Laplace transforms. But experience teaches us that there are often more direct ways of seeing **'What Must Be,'** just by thinking about the Fundaments."

There was that word again. "I have to tell you, Dr. Leif, that it was your passionate concern for what you call the Fundaments that most excited me during the interview! I want to spend my life thinking afresh about the Fundaments, as it is evident you have. Well, I confess that at first I cheated! I used the simulator, and this is what I found." Niku pulled up a waveform on her PDA, showing what happens when a current step of 0.909 mA with a 1-ps rise time is applied to a parallel tank of 20 nH (that is, L_1+L_2 in Figure 1) and 10 pF (C_T). The voltage immediately assumes a steady sinusoidal form, with a continuous amplitude of 40.65... mV (top panel, Figure 2). Furthermore, over many periods, the amplitude remains within much less than one part per billion, at 40.651715831... mV.

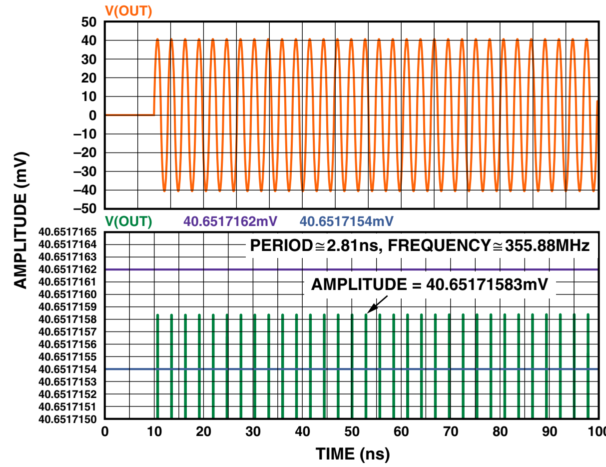


Figure 2. Result of applying a sudden step of current of 0.0909 × 10 mA directly to a tank of 2 × 10 nH and 10 pF. Niku's calculated amplitude is 40.65171583 mV. The vertically expanded trace (lower panel) showing the tips of the sine wave fully validates her theory. The added marker lines are at ±1 part per billion. This result incidentally illustrates the excellent conservation of charge provided by the GE°E simulator.

"GE°E gave me this result in less than a second," Niku enthused, "but my immediate instinct was to ask: 'Where does this funny number come from?' It implies that the tank presents a rather low impedance of (40.651... mV/0.909 mA), or 44.72135955... Ω, which is just another funny number. But doesn't a parallel-tuned tank exhibit an infinite impedance at resonance? And this tank was manifestly *resonating* in response to my stimulus!"

"Excuse me, Niku, but my TransInformer has just reminded me of a meeting, so I'm afraid I will need to leave in a few minutes. But before I go, I would like to say something about this notion that using a simulator is 'cheating.' Mathematicians once used to scorn 'numerical methods' as a way to gain insights, or to prove theorems. And any engineer who relied on 'computer-aided design'—in other words, simulation—to gain an understanding of circuit behavior was regarded by some as weak-minded and poorly equipped. But for decades we have viewed such methods in a very different light.

"Circuit designers once had to rely entirely on mathematics—and on their slide rule, pens and paper, and erasers—working through the night, fueled by endless cups of GalaxyBusters, because that was the *only way* of getting all the calculations done—like the way in which our transmobiles used to have four wheels and an engine that bravely managed to convert tens of thousands of explosions per minute into forward motion at 150 kilometers an hour on the old nonautomated MainWays. We simply didn't have anything better back in the 20th century.

"But we grew out of these things. Today, we no longer speak of computer-*aided* design, because so much of the old drudgery of calculation and optimization is managed by resourceful systems like GE°E. The equations in a modern simulator represent, in every important respect, an almost-perfect analog of the reality—whether a new molecule, a space elevator, or a clever circuit—and this allows us to examine numerous boundaries and optima to serve the *immediate* needs, while at the same time allowing us to gain

(continued on page 22)

The *nonslotted* aspect of the protocol means that EPs can transmit as soon as they have data, subject to first performing a *listen-before-talk* operation. This approach also ensures that no synchronization is required. If an EP senses the channel is busy, it backs off for a random period before performing another *LBT*. The number of times this back-off can occur is limited, hence the *nonpersistent* nature of the protocol. In FHSS mode, the protocol uses this CSMA-CA system on each hopping channel, thus fulfilling the LBT requirement for the new European regulations.

The *physical-layer* (PHY) and *media-access-layer* (MAC) parameters of the ADIismLINK protocol are highly configurable, thus allowing thorough device- and system evaluation. Source code is also provided, simplifying the system-development procedure. The protocol comes as part of the ADF702x Development Kit (ADF70xxMB2). A system overview of ADIismLINK is shown in Figure 6. More information on this is available through the ADI website (ADF702x Development Kit).[6]

CONCLUSION

The new European regulations impose very specific requirements for over-the-air protocols in the 863-MHz-to-870-MHz band. Whether a system uses a single-channel protocol, FHSS, or DSSS, there are specific rules that must be observed. This of course complicates the protocol design. However, the upside of these new ETSI regulations is that they mirror the FCC Part 15.247 regulations in many aspects, thus simplifying the design of a protocol intended for multiregion use. In addition, the Analog Devices development kit includes protocol examples to simplify the challenges involved in designing short-range wireless networks.

REFERENCES—VALID AS OF MAY 2006

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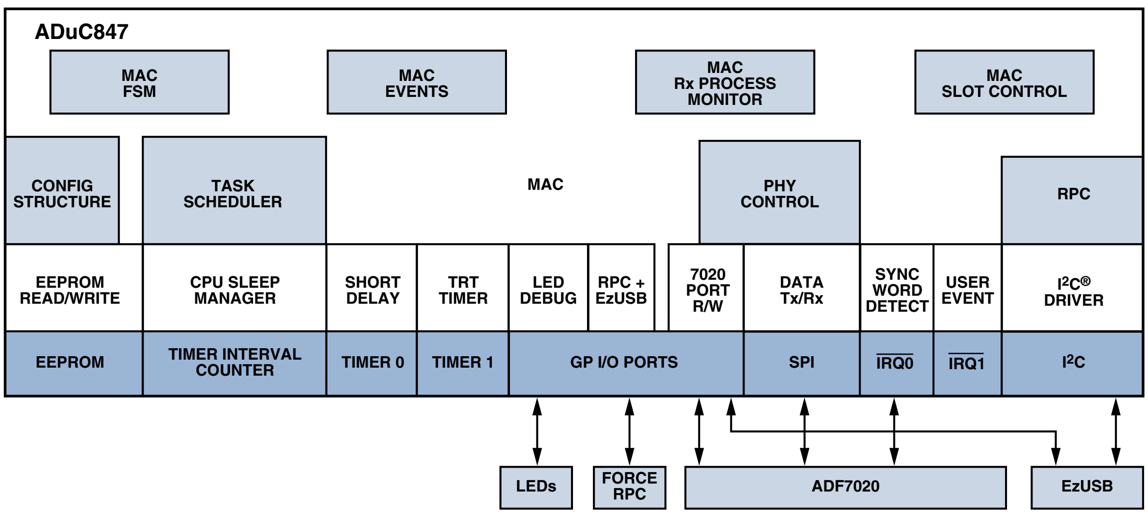

Figure 6. ADIismLINK system overview.

This article can be found at http://www.analog.com/library/analogdialogue/archives/40-03/wireless_srd.html, with a link to a PDF.

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immensely *deep insights*—far more quickly and clearly and accurately than classical mathematics ever could, with total control of all the conditions. For example, I expect you studied your oscillator's start-up trajectory (to use your nice descriptive word) at –50°C and +150°C, as well as somewhere in between, and had complete results for these conditions in seconds, right?"

"Yes, that's right, Dr. Leif. But the insights don't come directly from the machine. Even today's AI-rich simulators don't offer ideas! And the so-called genetic algorithms for circuit creation proved to be a great flop. *People* have the insights, and *people* create. I'd put it this way: *simulators stimulate solutions*. So, in this case, I found the tank appeared to have a small impedance, and GE°E gave me its value out to 20 decimal places. But now, with my curiosity stimulated, it was up to me to find the general solution."

"Exactly! You propose **'What If?'** and GE°E replies **'This will happen.'** Then you ask **'Why** does it do that? **How** did you get that value?' And these answers must come from thinking about the Fundaments—the **'What Must Be'** aspects of any circuit. GE°E is like a very willing and reliable, but junior, apprentice, who can calculate well but who cannot yet create. So, Niku, do you have the analytic solution, and how did you get it?"

"Oh, sure, that was one of the first things I took care of. Much more interesting insights came along later. Briefly, I thought of two ways of getting a general value for the impedance. Both rely on the **'What Must Be?'** philosophy. A simple tank only has two elements: an inductor and a capacitor. And there is only one way to get an impedance from these dimensional quantities—namely, by noting that $\sqrt{(L/C)}$ has the dimension of resistance. For our particular example of L = 20 nH and C = 10 pF, this evaluates to 44.721359549995796 Ω, which is precisely GE°E's answer! My second method is more roundabout."

"Niku, I really want to hear all the rest of your discoveries about this oscillator's behavior, but that will have to wait until our next visit. In the meantime, why don't you put your study notes up on ADI's CyberCyte? Hey, I'm proud of you already!"

As he was about to leave the table, he felt it appropriate to give his new protégée a fatherly pat on the shoulder.

(To be continued)