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Essentially, all models are wrong, but some are useful.

Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful.

— George E. P. Box and Norman R. Draper

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System Models in Wireless Sensor Networks

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Models play an important role in many different disciplines. The broad scope of applicability of models results in a wide range of *types of models* for a given system component, a *range of system components* that are of interest to be modeled, and an assortment of *levels of detail* provided in models. We introduce a classification system for models of networked embedded systems such as sensor networks, provide a taxonomy of existing research on models in terms of the presented classification framework, and highlight example applications of models in the research literature. Based on the insight gained in developing the classification framework and taxonomy, we discuss possible future modeling directions in the area of wireless sensor networks.

Categories and Subject Descriptors: C.4 [**Performance of Systems**]: Modeling Techniques

General Terms: Design, Measurement, Performance

Additional Key Words and Phrases: Wireless Sensor Networks, Models, Optimization, Tradeoff Analysis

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1. INTRODUCTION

Complex hardware-software systems such as wireless sensor networks are best evaluated with actual deployed hardware and software, as they often involve complex interactions between system components that are difficult to capture completely with evaluation techniques such as simulation. The creation and deployment of complete systems is, however, costly, time consuming, and requires a substantial amount of domain expertise. Due to these and other challenges posed by developing, deploying, and evaluating hardware and software, it is often desirable to capture properties and behaviors of particular aspects of a system with *models*—abstractions or representations of a system in an alternative form that is more amenable to a set of tasks at hand. If these models can be shown to be good surrogates or predictors of the system properties they abstract, and if they provide a cheaper (lower cost, less time-consuming) means of evaluation, they can be used in place of the entities they abstract, to the benefit of the research process.

Models of a system may take many forms, and may be categorized by many different criteria. For example, models may be characterized by how closely their *structure* matches that of the system they model, regardless of other properties of the model. There are many issues that must be taken into consideration when employing models of various sorts as surrogates for the systems they represent. These issues include *accuracy* (how closely do the models mirror actual behavior ?) and *performance* (how much time or computation does the use of the model involve ?). In some applications, it might be desired for models to predict precise values of system outcomes, while in others, it might only be required that they exhibit the same *trends* as the systems they model; as a result, the desired application domain of models often influences their form. In the case of application of models to quantitative analysis and prediction, models will likely be calibrated with *concrete values* from, say, hardware and software system measurements. For use in qualitative comparisons however, non-calibrated models employing *abstract values* might be acceptable.

This paper surveys the spectrum of models proposed in the wireless sensor network literature, ranging from models of signal propagation and reflection or absorption by objects, to models of applications and the phenomena they monitor or are driven by. Relevant terminology and background is introduced in Section 2. It is followed in Section 3, by a classification system distinguishing the form taken by models, the manner in which they are constructed, the network abstraction layer to which they are targeted, and the system properties or metrics they capture; a survey of the recent literature pertinent to models and their applications in wireless sensor networks is presented in the context of this classification. Relevant modeling tools are surveyed in Section 4, and Section 5 discusses challenges and possible directions for the future of models and their applications in wireless sensor networking research.

2. MODELS

Models, in the context of computing systems research, may be defined as *abstractions of the functional behavior of a system or entity, in a form amenable to simulation or analysis*. The term *evaluation metric*, or simply *metric*, is usually used to denote aspects of a model that may be measured, or quantities that a model predicts. The variables and constants that affect the behavior (or nature) of the model, are usually referred to as its *parameters*.

2.1 Parameters

The behavior of a system (and of its model) is a function of its parameters. The parameters may be set at design time, in which case they may be considered as fixed *resources* (e.g., energy, time or available clock cycles per second), or they may change after a system has been implemented or deployed, e.g., packet sizes chosen at the point of initiation of a communication.

Some parameters may be constants which influence the behavior of the system but remain fixed either due to being a physical constant (e.g., the speed of light, the amount of energy needed to form an electron-hole pair in silicon, and so on), or a design-time constant (e.g., a system's operating voltage). Other parameters may vary over the lifetime of the system. For example, packet sizes in data transmission are a parameter whose value may be determined when a packet is created, and play a role in a system's energy model. A parameter may also be out of the control of a user of the system. For example, atmospheric temperature may vary over time, and can affect power dissipation, clock drift, and battery life, but typically cannot be controlled by a system designer or deployer. These ideas are illus-

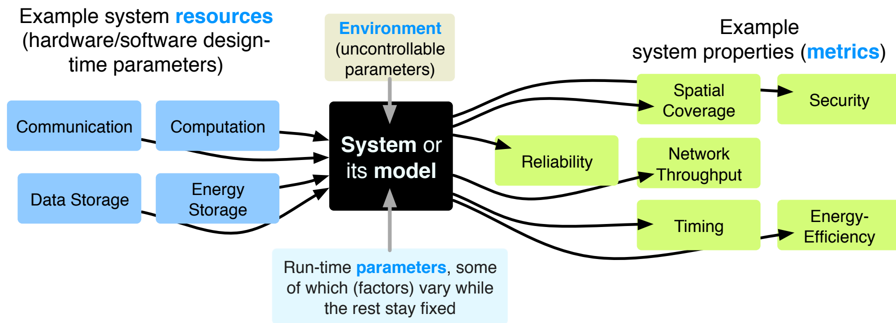


Fig. 1. Entity behavior, as a function of design-time resources (hardware, software or physical limit constraints and parameters), and system parameters, determine the observed system behavior with respect to *evaluation metrics* / *system properties* of interest.

trated in Figure 1. Controllable parameters may include items such as hardware mode settings, protocol parameters, or application parameters. Uncontrollable parameters (such as atmospheric temperature) on the other hand, may typically be regarded as elements of the *environment*. Parameters might permit independent control of system properties or their effects might be correlated. It is therefore often of interest in the study of models of system behavior, not only to identify the parameters, and their influence on system metrics via models, but also to determine the *correlations* between metrics of a system, due to dependencies between model parameters. Such analysis falls under the research areas of *factor analysis* and principal component analysis [Gorsuch 1983].

2.2 Metrics

In common usage, the term "metric" is used to refer to an evaluation criterion or property used to judge the quality of a system, such as its *energy-efficiency* (e.g., average power dissipation or energy usage for a given task), *timeliness* (e.g., delay or latency for a given operation), its *dependability* (an umbrella term that captures several concepts relating to reliability) [Laprie et al. 2004], or *security* (e.g., computational or energy cost for a brute-force attack on a cipher).

Metrics in wireless sensor networks range from metrics for the energy efficiency of radio communication interfaces [Ammer and Rabaey 2006], to metrics for quantifying the performance of routing protocols [Qin and Kunz 2006; Park and Kasera 2005; Zuniga and Krishnamachari 2004b; Li et al. 2005], metrics characterizing properties of an entire network, such as its *reliability* or *visibility* [Wachs et al. 2007; Hao et al. 2004], and metrics specific to certain application behaviors, such as quantifying the effectiveness of a spatial mapping application [Nordio et al. 2007]. The importance of a consistent set of metrics and system parameters when establishing a set of benchmarks for the evaluation of wireless sensor networks, has been discussed in detail in [Corbett et al. 2006]. Several metrics of relevance in wireless sensor networks, brief explanations of their formulations, and example values, are listed in Table I.

The lifetime of a network may be represented as the time until the first node dies, the time until the last node in the network depletes its energy resources or

Table I. Examples of metrics of relevance in wireless sensor networks.

Metric	Comments	Example Value
Energy per useful bit [Ammer and Rabaey 2006]	Captures overhead due to physical layer modulation.	Approximately 300 nJ for a CC2420 transceiver, when using 12 byte packets.
Expected data rate [Park and Kasera 2005]	Captures the effect of per-hop contention on multi-hop throughput.	E.g., 50 kb/s.
Single-hop latency	Time from transmit attempt, to receipt, across a single hop.	>3 ms for 100 byte packets on a CC2420 transceiver. Actual time depends on system software, prior mode of transceiver, etc.
End-to-end latency	Time from transmit attempt, to receipt, across multiple hops.	>15 ms for a five hop network, based on the above.
Energy per instruction	Dependent on architecture, and implementation; effective amount of computation in one instruction differs across microcontrollers/processors.	0.594 nJ for TI MSP430F2274.
Visibility [Wachs et al. 2007]	Defined as the energy cost of diagnosing the cost of an observed protocol behavior.	E.g., $> 9.1\,\mu$J if it takes the transmission of ten 128 byte packets and execution of 10 k instructions to diagnose a behavior (from the above).

fails catastrophically for some other reason, or some other function of the distribution of dead and alive nodes and links. For example, another measure of network lifetime is the time until network *partition*, i.e., time until the network splits into two or more non-communicating groups. If the real-time capacity of a network is to be studied, metrics such *end-to-end delay* or *one-hop delivery delay* arise. Once again, the properties of interest are usually some function of the distribution of per-hop or end-to-end latencies. If one defines a random variable X to denote the number of packets delivered in a one second time window, then, statements such as "90% of packets delivered in less than one second" or "nine out of every sequence of ten packets arrive in less than one second" define the correct behavior of the network, as a constraint on some function of the random variable X; the first expression allows the first 10% of the total traffic generated to be delivered late and the remaining 90% be on time, while the second expression forces a distance of at least nine packets delivered in time, between two late packets. The per hop and end-to-end latencies of a network will also affect the detection latencies [Chin et al. 2006] for phenomena being monitored by a network.

2.3 Metrics and parameters linked across abstraction layers—cross-layer models

Metrics and parameters in modeling go hand-in-hand. In systems comprising models at different layers of abstraction, the evaluation metrics of a lower abstraction layer may serve as the input parameters for a higher layer, as illustrated in Table II. In the table, a simple stacking of an application over a medium access control (MAC) protocol, stacked in turn over a physical (PHY) layer implemented in a transceiver, is illustrated. In the example, the *metrics* of a model of the transceiver, capture its average power while in transmit (TX), receive (RX), idle listening and power-down states, and these serve as *parameters* for an energy model

Table II. Example of the possible interlinking between parameters and metrics across models for different network abstractions layers.

Network Abstraction Layer	Parameters	Metrics
Physical (PHY) layer / transceiver (e.g., TI CC2420 IC)	Radio transmitter power configuration (e.g., 0 dBm)	TX, RX, listen, power-down power dissipation
Medium access control (MAC) (e.g., IEEE 802.15.4 MAC)	PHY TX, RX, listen and power-down power, min. backoff exponent, max. # backoffs	Energy per useful bit, MAC bytes per application byte
Application + network	Energy per application (useful) byte, MAC bytes per app. byte, app. duty cycle	App. energy per second (average power)

for the MAC, in addition to MAC-specific parameters. The metrics of MAC layer behavior, the energy expended per payload bit and MAC communication overhead (e.g., RTS/CTS and ACK frames) in turn serve as parameters of application energy models, alongside application-specific parameters such as the application's duty cycle. Models which capture properties of different network abstraction layers in such an interconnected manner are referred to in this survey as *cross-layer models*.

The preceding example also alludes to potential problems that may arise when attempting to characterize properties of protocols at higher abstraction layers—the observed behavior will be a function of the behavior of lower abstraction layer protocols, and it is not always straightforward to isolate these effects in order, for example, to build regression models of higher-layer protocols.

2.4 Models in computing systems research

The idea of models for various aspects of a system permeates all areas of computing systems research. At the lowest hardware layers, models are used for the study, for example, of the interaction between molecules of the materials involved in chemical-mechanical polishing processes in semiconductor device manufacture. While these processes could in principle be studied with tools such as atomic force microscopes (AFMs), such studies would not be feasible due to the time and costs involved, as well as due to the lack of scale (studying individual pairs of molecules versus large volumes of material).

At a higher layer of abstraction, models are heavily employed in the study of electrical circuits. These models, which are often in a form for use in the ubiquitous SPICE circuit-level simulator [Nagel and Pederson 1973], enable the modeling of circuits ranging from simple passive networks to complex integrated circuits. Existing models range from those for various fundamental circuit components, such as the Ebers-Moll or Bummel-Poon models for bipolar junction transistors [Sze 1981], to models for complete integrated circuits such as operational amplifiers [Texas Instruments, Inc. 2008] and voltage regulators [Linear Technologies, Inc. 2008]. Once again, while these systems could actually be built and their properties measured, accurate models enable the study of the behavior of circuits under different *circuit parameters* and *environmental operating conditions*, and to do so without the need to build (or prior to building,) prototype hardware.

As yet another example, in the study of wireless networks, there exist various models for approximating the propagation of electromagnetic signals, resulting from a combination of empirical observations and an understanding of the properties of electromagnetic fields and waves [Tse and Viswanath 2005]. There are likewise models for the behavior of networks of computing systems communicating over wireless channels, to enable prediction of the intricate communication patterns that may exist resulting from interactions between low-level radio properties, application behaviors, usage models, mobility, and so on. Although the behavior and properties of systems such as sensor networks may be observed directly via measurements on real systems, models enable, for example, quick estimation or prediction of the behavior of large networks prior to their construction. As a final example, models may also be used to drive the inputs to systems during testing. For example, models of network traffic patterns are often used in the analysis of networked computing systems.

Specific examples of applications of models in wireless sensor networking research, include predictive analysis and single-objective optimization [Curescu 2005; Drinic et al. 2003; Wark et al. 2007; Mukhopadhyay et al. 2004], and multi-objective optimization or tradeoff analysis [Hoes et al. 2007; Sadler and Martonosi 2006; Mostofi et al. 2005]. For example, [Hoes et al. 2007] use closed-form analytic models for reliability of single and multi-hop links, as well as deterministic closed-form analytic models for energy, spatial coverage and timing of an application, to drive tradeoff analysis.

3. A CLASSIFICATION SYSTEM FOR SENSOR NETWORK MODELS

Models used in computing systems may be classified along many different axes, including the *form* (the manner in which metric values are computed from the model given a set of system parameters and resources), *construction approach*, and *application-(sub)domain*, as well as the *metrics* which they predict.

3.1 Analytic versus behavioral models

In the broadest sense, models may be characterized as either mathematical or *analytic* models expressed as collections of equations, or as *interpreted* or *executable* models, intended as input to simulation tools, or which are otherwise evaluated by *walking* the model through a sequence of states. Analytic models may be *closed-form expressions*, in which constants can be substituted and the expressions evaluated without iteration or recursion, or they may be analytic expressions for, e.g., the *next-state equations* for a deterministic *state machine* or *behavioral* model, or the *balance equations* or *difference equations* for a stochastic Markov model; executable or interpreted models are however implicitly always behavioral models. This top-level organization of the *structure* of models is illustrated in Figure 2.

3.2 Bottom-up construction (“white-”/“clear-box”) versus black-box models

A variety of *construction approaches* may be employed in the creation of models. One classification of construction approaches is with regards to whether they are built to estimate high-level system properties from low-level ones (e.g., estimating end-to-end communication latencies from lower-layer models of computation latencies and radio transmission delays), or whether they are used to estimate system-level metrics for one system configuration, based on properties of

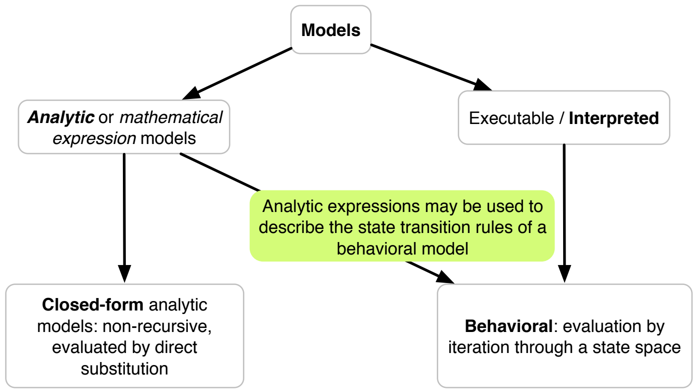


Fig. 2. Possible coarse-grain *structural forms* of models discussed in this survey.

the system for another system configuration. The former types of construction approaches may be referred to as *bottom-up* (or alternatively as "white-" or "clear-box" construction approaches), and the latter *black-box*. The black-box approach to modeling is often carried out by *regression analysis*, while the bottom-up approach is often a result of the consideration of the construction of a system *from first principles*, i.e., based on an understanding of the fundamental components of the system and the manner in which they behave individually, and interact as a system. Another aspect of the manner in which models are constructed is whether they are intended for the prediction of absolute values (and hence are calibrated with *concrete values*), or whether they are intended only for relative comparisons (and hence only involve relations of *abstract values*).

An example of a bottom-up approach is the construction of a model for end-to-end latency of a network as a function of known MAC-layer (per-hop) latencies, known channel access behavior (e.g., contention resolution mechanisms), and per-hop delivery reliability. A black-box model on the other hand might attempt to create a model for the end-to-end latency directly by performing end-to-end latency measurements under different network configurations (a combination of parameter settings at the various network layers), and building a model by regression analysis on the measurement data and the configuration parameters.

3.3 The classification system

The discussions of model classifications and attributes of the preceding sections are distilled in the multi-dimensional classification space illustrated in Figure 3. The four dimensions are *application domain* (**D**), *model structure* (**S**), *construction approach* (**C**) and *metrics* (**M**), and a given model has an interpretation along *each* of these axes. In each dimension, the possible entries are a totally ordered set, with mutually exclusive properties (shown in the figure with a "⌙") labeled in counting order from 1; properties which are not relevant for a given dimension, or which are otherwise unknown are given the label numbering 0. This labeling can be used as a concise description of a model. For example, a physical-layer radio model (**D2**), that is in the form of closed-form analytic expressions which are deterministic in

Table III. The shown operations per second are the corresponding instruction throughput for the presented energy per instruction, with the maximum throughput shown in parenthesis if different.

Microcontroller	Operations per Second	Energy per Operation
Atmel ATmega128L [Atmel, Inc. 2006a]	16E6	10156 pJ
TI MSP430F1232 [Texas Instruments, Inc. 2003]	1E6(8E6)	440 pJ
TI MSP430F2274 [Texas Instruments, Inc. 2006]	1E6(16E6)	594 pJ
TI MSP430F149 [Texas Instruments, Inc. 2004]	1E6(8E6)	616 pJ
Atmel AT91SAM7S512 (ARM7TDMI) [Atmel, Inc. 2006b]	55E6	1963 pJ

their formulation (**S21**), constructed from first principles based on a knowledge of the behavior of hardware, and calibrated with measurements of concrete values on actual hardware (**C11**), and which predicts energy consumption (**M5**), will be labeled as a **D2S21C11M5** model. In some cases, it is convenient to only refer to the classification of a model along a subset of the dimensions, and in such cases dimensions can be omitted. For example, to indicate network layer models of any kind, one may simply refer to "**D4** models".

The notation is also extensible. New entries may be added to a dimension, e.g., one may in the future have reason to add a sixth entry, **M6** to the metrics dimension. New sub-dimensions may also be created, e.g., splitting up the **D1** dimension (hardware models) into computation models (**D11**), sensor access models (**D12**), radio hardware models (**D13**), energy source models (**D14**) and clock drift and oscillator models (**D15**)[1]. If one were to wish to extend both the **D** dimension (for, say, a **D10**) as well as create new sub-dimensions of a dimension (say, **D1** as in the preceding example), one may represent values larger than 9 as hexadecimals, such that the encoding retains its one-digit-per-dimension property. Further examples of instances of entries in different classifications will be provided in the remainder of the survey (with decreasing frequency, in order not to unduly clutter the text).

3.4 Node hardware models

The hardware platforms employed in any application domain, and in sensor networks in particular, have a significant (and obvious) impact on application performance. Limitations of hardware dictate limitations of the systems in which they are used, and likewise inaccurate hardware models, when employed in making predictions of whole-system behavior, may lead to incorrect predictions of behavior, or of evaluation metrics.

3.4.1 *Computation latency and energy cost models.* While the power dissipation in many wireless sensor systems may be dominated by the radio communication interface, other system components such as the compute resources may also contribute to a considerable fraction of a system's power dissipation, in addition to playing an important role in the performance of applications. Models for computation in sensor platforms have typically focused on closed-form expressions (or constants) for the power dissipation associated with computation [Qin Wang; Hempstead 2006], with behavioral models typically em-

[1]While we do make these specific distinctions for **D1** models in this survey, we do not perform such further subdivision of the **D1** models.

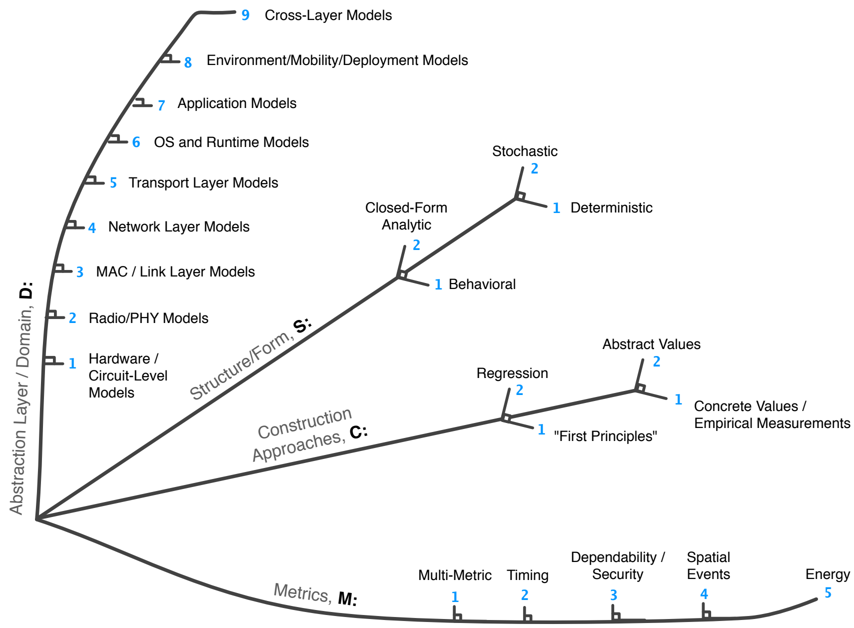


Fig. 3. The properties of models of networked computing systems may be classified along the multiple dimensions shown here. In a given dimension (e.g., model structure), sub-dimensions are often orthogonal (e.g., closed-form analytic versus behavioral models).

ployed for estimating the latency associated with computation [Titzer et al. 2005; Fraboulet et al. 2007; Stanley-Marbell and Marculescu 2007].

Although it typically varies across the instructions in a given instruction set architecture (ISA), the delay associated with most instructions in the ISAs of the low-end microcontrollers typically employed in sensor networks can be assumed to take on a single value. Across hardware platforms however, there are differences in processing capabilities. Table III lists the delay and energy cost per instruction for several microcontrollers employed in contemporary sensor platforms. Each row in the table can be seen as providing a basic timing and energy model (**D1S21C11M2** and **D1S21C11M5**) for the computation occurring in a system.

3.4.2 *Sensor access energy and delay.* A predominant function of sensor networks is the monitoring of the evolution of phenomena in their environments, and this is achieved through the use of sensors of various kinds. Examples of sensors include temperature and humidity [Sensirion 2007], pressure [VTI Technologies 2007], and light / color [TAOS, Inc. 2005]. Sensors are interfaced to the processing elements that drive nodes through either analog or digital interfaces. Analog interfaces typically involve a sensor output voltage proportional to the sensed phenomenon, and may require the use of additional signal conditioning circuitry (amplification, filtering) prior to analog-to-digital conver-

Table IV. Sensor delay and power dissipation costs for several contemporary sensors used in wireless sensor node platforms.

Sensor	Interface	Avg. Power for sense/op.	Delay per sample
Temperature [Sensirion 2007]	Custom Digital	2.75 mW	210 ms
Pressure [VTI Technologies 2007]	SPI	0.075 mW	10–1000 ms
Humidity [Sensirion 2007]	Custom Digital	2.75 mW	55 ms
Color [TAOS, Inc. 2005]	Custom Digital	10 mW	100 μs from power-down
Acceleration [Analog Devices, Inc. 2004]	Analog	0.84 mW	20 ms from power disconnect
Digital Compass [Honeywell 2006]	I2C	3 mW	6 ms
GPS [Tyco Electronics 2007]	UART	108 mW	1–35 s

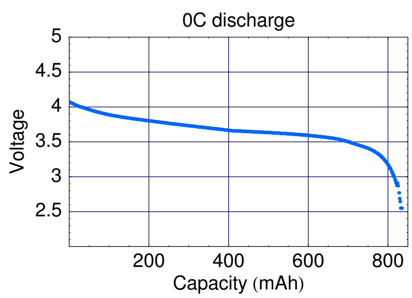
sion. Such conversion is typically performed within the microcontroller, using internal ADCs, but may also be performed off-chip using dedicated ADCs. Digital interfaces include the use of the serial peripheral interface (SPI), inter-integrated circuit (I2C) bus, the use of a universal asynchronous receiver/transmitter (UART) interface, or the use of a custom digital signaling interface. The access of a sensor via any of these analog or digital interfaces has a cost, comprising the costs of actual sensor operation, as well as acquisition of the sensor reading by the microcontroller. Examples of the costs of sensor access, as well as details of their interfaces, for several commercially-available sensors typically employed in sensor networks, are shown in Table IV. Each row of Table IV can be considered as the concrete values for **D1S21C11M5** and **D1S21C11M2** models of sensor energy and delay, respectively, per sampling event.

3.4.3 *Radio hardware / transceiver models.* The modulation of data for transmission over a physical communication medium (e.g., in the context of this survey, RF signals), is typically achieved in contemporary hardware platforms, using an integrated circuit known as a *transceiver* (an agglomeration of *transmitter* and *receiver*); examples of currently popular transceivers include the CC2420 from Texas Instruments [Texas Instruments, Inc. 2007b], and the MC13192 from Freescale Semiconductors [Freescale Semicondictor, Inc. 2007].

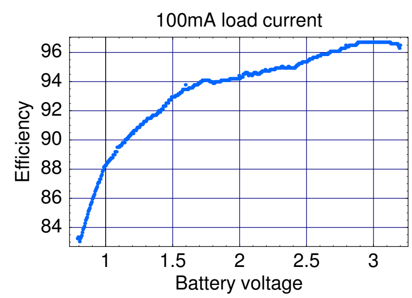
A substantial fraction of the power dissipation (and a large fraction of network latencies) of wireless sensor node platforms occurs in the node's communication radio subsystem, particularly, in the system's transceiver and associated circuitry. This makes it desirable to have models for the transceiver's timing and power dissipation characteristics. Typical characteristics of a transceiver's energy and delay characteristics are its *power dissipation* at different *transmitter power levels* (specified in dBm, a logarithm of the transmitter power in milliwatts), receive and idle listening power dissipation, bit rate, and receive sensitivity (which defines the minimal signal strength that can be correctly de-modulated at a given bit error rate). Each such collection of parameters for a radio may be used to form a simple transceiver power (**D1S21C11M5**), timing performance (**D1S21C11M2**) or reliability (**D1S21C11M3**) model; a collection of such transceiver properties for several of the most popular state-of-the-art transceivers operating in the unlicensed 2.4 GHz industrial science and medicine (ISM) band are listed in Table V. To better model energy consumption, recent transceiver models take into account not only operating states such as sleep, transmission and reception, but also transient states

Table V. Power dissipation and receive sensitivity characteristics for the most common contemporary transceivers and transmit-only RF integrated circuits for the 2.4 GHz Industrial Science and Medicine (ISM) band. The values are taken from the respective manufacturer data sheets for the devices in question. Each row of the table can be considered as the *concrete values* used as coefficients in a simple **D1S21C11M5** (energy model) or **D1S21C11M3** (reliability model, constructed in conjunction with channel models,) for the transceiver(s) in question.

Transceiver	PHY/Modulation	Nom. TX Current	Min. RX Current	Standby Current	Max RX Sensitivity
Freescale MC13191/13201	802.15.4 (DSSS)	30 mA, 0 dBm	37 mA	1 μA	-91 dBm
Freescale MC13192/13202	802.15.4 (DSSS)	30 mA, 0 dBm	37 mA	1 μA	-92 dBm
Ember EM250/EM260	802.15.4 (DSSS)	35.5 mA, +3 dBm	35.5 mA	1 μA	-98.5 dBm
Atmel AT86RF230	802.15.4 (DSSS)	16.5 mA, +3 dBm	15.5 mA	0.02 μA	-101 dBm
TI CC2430/2431	802.15.4 (DSSS)	27 mA, 0 dBm	27 mA	0.5 μA	-92 dBm
TI CC2420	802.15.4 (DSSS)	17.4 mA, 0 dBm	18.8 mA	0.02 μA	-95 dBm
TI CC2520	802.15.4 (DSSS)	25.8 mA, 0 dBm	18.5 mA	0.3 μA	-98 dBm
TI CC2510Fx/CC2511Fx	2-FSK/GFSK/MSK	26 mA, 0 dBm	17.1 mA	0.5 μA	-103 dBm
TI CC2550	OOK/2-FSK/GFSK/MSK	19.4 mA, 0 dBm	TX-only	0.2 μA	TX-only
TI CC2500	OOK/2-FSK/GFSK/MSK	21.2 mA, 0 dBm	13.3 mA	0.4 μA	-99 dBm
TI CC2400	FSK/GFSK	19 mA, 0 dBm	24 mA	1.5 μA	-101 dBm
Nordic nRF24L01	GFSK	11.3 mA, 0 dBm	11.8 mA	0.90 μA	-85 dBm
Nordic nRF24LU1	GFSK	11 mA, 0 dBm	12 mA	480 μA	-85 dBm



(a) Battery terminal versus state of charge curve for a Panasonic CGR17500 Lithium ion battery [Panasonic, Inc. 2000].

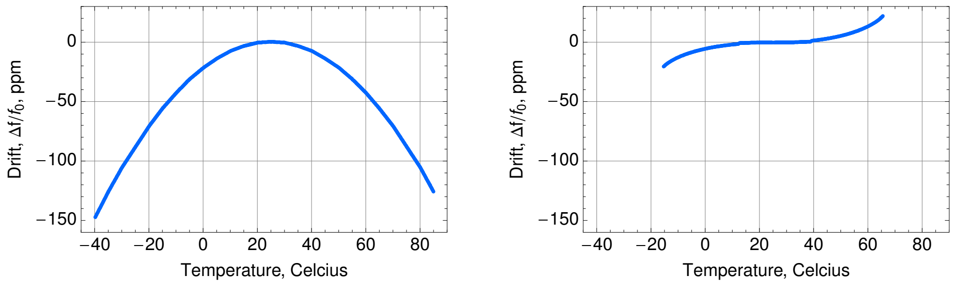


(b) Voltage regulator efficiency curve for a TI TPS61100 voltage regulator [Texas Instruments, Inc. 2002].

Fig. 4. Example characterization properties for actual batteries and voltage regulators that may be used in wireless sensor node platforms.

such as sleep to reception, transmission to reception, and so on [Howitt et al. 2005; Wang and Yang 2007]. While radio hardware / transceiver models are often created separately from radio channel models, there is occasionally the need to consider interactions between properties of the radio hardware (e.g., transmit power) and its interaction with the environment [Myers et al. 2007] or with other transmitters [Son et al. 2006].

3.4.4 *Energy delivery subsystem models.* The energy sources that power sensor platforms have many non-linear properties that make the prediction of their ability to deliver energy a non-trivial matter. As a result, there is great interest in being able to accurately model such subsystems, in order to accurately predict their behavior. Models for energy sources range from models for estimating the state-of-



(a) Typical crystal drift with temperature for a low-frequency (32.768 kHz) quartz crystal, part number S3883-32.768K [Pletronics, Inc. 2005].

(b) Typical crystal drift with temperature for a high-frequency (16 MHz) quartz crystal, part number ECX-3S-16MHz [ECS, Inc. 1999].

Fig. 5. Crystal drift with temperature, for a low-frequency crystal (typically used for a node's microcontroller), and a high-frequency crystal (required by many radio transceivers).

charge of batteries under different load current profiles, as well as effects such as self-discharge and self-recovery [Behrens et al. 2007; Chulsung Park; Lahiri 2005; Benini et al. 2000; Rakhmatov et al. 2002], to models for the voltage regulators that are necessary to provide stable voltage levels in in the face of falling battery voltage levels.

Such energy source models capture the relation between the effective energy store capacity at a given node, and the distribution of system power consumption over time, and are a function of battery type (e.g., Li Ion, NiMh, Li polymer, supercapacitor or Zn Air). They also depend on the efficiency of the voltage regulators necessary to provide a stable voltage to power the system, from the battery terminal voltage which declines with battery discharge. An example of the battery terminal voltage versus state of charge properties for a Lithium ion battery is shown in Figure 4(a), and an example voltage regulator efficiency curve is shown in Figure 4(b).

3.4.5 *Clock drift and oscillator models.* A major cause of the uncertainty in wireless sensor networks, and hence the difficulty in modeling them, is due to variations in the properties of the environments, but also in the properties of hardware. In particular, the notion of *time* is affected by drifts in crystal-driven oscillator frequencies, compounded by the frequent transitions of nodes between active and sleep modes. Figure 5 illustrates the drift in frequency for two crystals—a low-frequency 32.768 kHz quartz crystal typically used to provide a clock reference for microcontrollers, and a high-frequency 16 MHz quartz crystal. These characteristics may be used in a model of clock drift, alongside models of temperature fluctuations, to model oscillator and time-based drift. Attempts to enable modeling of clock uncertainty under such conditions include [Ganeriwal et al. 2005; Arfvidsson et al. 2006].

3.5 Radio signal propagation / channel models

Radio signal propagation models or *channel models* also play an important role in the modeling of wireless sensor networks. Channel models typically provide models for signal *fading*, the attenuation of transmitted signals over space, time, or other dimensions. Fading has traditionally been classified as either *large-scale fading* (resulting from properties of the environment, such as the presence of walls and other obstacles), and *small-scale fading*, due to the interference between signals and their own reflections. Many aspects of large-scale fading in this survey will be covered separately under the discussions of environment models in Section 3.10.

Wireless sensor node platforms communicate almost exclusively by radio frequency (RF) signals, as opposed to other "wireless" communication media such as ultra-sound or infra-red. There are a variety of communication carrier frequencies used in the RF communication interfaces in wireless sensor networks, including the 300–348 MHz, 387–464 MHz and 779–928 MHz bands in the sub-1 GHz spectrum [Texas Instruments, Inc. 2007a], and the 2.4–2.5 GHz band. Alongside these different carrier frequencies are a range of modulation techniques, including, *amplitude shift keying (ASK)*, *binary frequency shift keying (2-FSK)*, *binary phase shift keying (BPSK)*, *frequency shift keying (FSK)*, *Gaussian shaped frequency shift keying (GFSK)*, *minimum shift keying (MSK)*, *on-off keying (OOK)*, *quadrature phase shift keying (QPSK)* and *orthogonal quadrature phase shift keying (O-QPSK)*.

For each of these carrier frequencies and modulation techniques, models may be created for the properties of the transmitted signal over space. Examples of properties of interest include the *path loss*—the signal attenuation with distance—and the *bit error rate (BER)* for a given *signal to noise ratio (SNR)* or *signal to interference plus noise ratio (SINR)*. A simple model for the attenuation of signal strength, at distances d much larger than the carrier wavelength, defines the received signal power as proportional to [Tse and Viswanath 2005]

$$\frac{1}{d^2} \quad \text{(in free space)},$$
$$\frac{1}{d^4} \quad \text{(considering ground reflections)}.$$

As a concrete example of the above, the Friis free space model defines the receive signal power, P_R for carrier wavelength λ, a receiver with receive antenna gain G_R, at distance d from a transmitter with transmit power P_T and transmit antenna gain G_T, as

$$P_R(d) = \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 d^2}.$$

The above simple models however neither take into account the constructive and destructive interference of signals emanating from a transmitter, which, in real-world, non-free-space environments, may be reflected off objects in the surroundings of the transmitter. Relative motion of transmitters and receivers, which leads to Doppler spread, is also not accounted for in such simple models. Such simple models further do not take into account the energy and latency overheads of typical transceivers in use in sensor networks, which dominate the power dissipation (and hence the power required to reach a given distance) [Min and Chandrakasan 2003].

The properties of various portions of wireless sensor network systems, and signal propagation in particular, are well enough understood to enable precise solution for metric values for a given set of system parameter settings; the challenge, however, is one of computational efficiency and expediency. For the signals emanating from transmitters and impinging on receivers for example, one might proceed by solving Maxwell's equations or employ *radio signal ray-tracing* approaches. These techniques may be employed alongside antenna models, models for the reflective and absorptive properties of objects known to be present in the deployment environment, and the effects of motion of these objects as well as the communicating entities (leading, e.g., to Doppler spread). While *possible*, such approaches are not computationally attractive. Instead, it is sometimes enticing to employ *stochastic models*, e.g., replacing the use of detailed models of individual objects with notions of object density distributions, and modeling signal scattering with appropriate stochastic processes. Concrete examples of such stochastic models are the Rayleigh, Log-normal and Rician fading models for signal propagation [Tse and Viswanath 2005], and the Gilbert-Elliot channel model [Wang and Moayeri 1995; Gilbert 1960]. In these models, the *probability space* on which the stochastic model is defined consists of a sample space of elementary events being the signal attenuation degrees at a given radial distance from a transmitter, and the probability measure assigning probabilities to the events that attenuation takes on specific values.

For a given modulation scheme, and as a function of SNR, there also exist models for probability of bit error. For BPSK modulation, the probability of bit error, p_e (assuming that a Rayleigh fading model accurately describes the channel properties) depends on the SNR per modulated symbol signal at the receiver, as (from [Tse and Viswanath 2005]):

$$p_e = Q\left(\sqrt{2\,SNR}\right),$$

where Q is the complementary cumulative distribution function of a random variable following the standard normal (zero mean, unit variance) distribution, $N(0,1)$. As another example, for a *direct-sequence spread-spectrum (DSSS)* system with BPSK modulation, a Rake receiver with L diversity branches, and with a Rayleigh fading channel, the error probability is given by Tse and Viswanath [2005] as

$$p_e = \left(\frac{1-\mu}{2}\right)^L \sum_{l=0}^{L-1} \binom{L-1+l}{l} \left(\frac{1+\mu}{2}\right)^l,$$

where

$$\mu = \sqrt{\frac{SNR}{1+SNR}}.$$

The former models of received signal power can be combined with models of interference and channel noise to obtain models of SNR at a receiver, and hence of bit error rates. These models may even further be incorporated into models of medium-access control behavior (e.g., per-hop retransmissions), and so on.

Radio signal propagation properties have been well studied for many years, in the context of cellular and ad hoc wireless networks, and many of these results carry over to wireless sensor networks. Detailed coverage can be found in the literature [Willis and Kikkert 2005; Scott et al. 2006; Zhou et al. 2006; Tse and Viswanath 2005], and [Rao 2007] provides a concise summary from the viewpoint of transmission range of IEEE 802.15.4 physical layer radios. Specific models for channel fading and shadowing losses can be used [Studedi and Alonso 2007], and models exist for various forms of path loss [Inaltekin and Wicker 2007], distribution of received power over time and space [Salbaroli and Zanella 2006; Wong and Cruz 2006; Zuniga and Krishnamachari 2004a; Zhou et al. 2004].

Channel models also play a role in the evaluation of node localization techniques, as it is necessary in those studies to have accurate models for the attenuation of radio signals in a given environment. The effects of model accuracy on localization can be seen in [Whitehouse and Culler 2006; Whitehouse et al. 2005; Elnahrawy et al. 2004]. As they often define the non-idealities in signal propagation in environments, channel models are also of importance in modeling communication failures [Cerpa et al. 2005; Srinivasan et al. 2006; Das et al. 2005]

The channel models in many behavioral simulations of other layers in wireless sensor network protocol stacks are often, however, a simple inverse quadratic path loss model, such as that shown earlier in this section. Example uses of such simple models include the default channel model provided by the *mobility framework* extension of the Omnet++ simulator [Varga 2001]. Part of the difficulty in employing more realistic channel models may be due to the fact that the properties of the channel depend heavily on the deployment environment (walls, stationary and moving objects, etc.), thus many researchers resort to simple models with a single parameter(radial distance from the transmitter). Research directions in modeling the details of the properties of the environment, such as its noise properties [Lee et al. 2007] and signal attenuation properties are thus a promising future direction. Environment and deployment models are discussed further in Section 3.10.

3.6 Medium access control and link layer models

Unlike physical layer property models and transceiver hardware models, whose counterparts in actual implementations are typically hardware systems (integrated circuits), medium access control (MAC) and link layers are usually implemented, at least in part, in software. It has thus been enticing for researchers to use such actual software implementations (or their precursors), as the basis of modeling activities, e.g., by simulating the actual deployment code over instruction-level simulators or emulators, or compiling against emulation environments such as TOSSIM [Levis et al. 2003] and its derivatives. As a result, many MAC and link layer models described in the literature are behavioral simulation models.

A small number of medium access control (MAC) protocols for wireless sensor networks have both deployable implementations and either behavioral or closed-form models [Bougard et al. 2005; Tseng et al. 2004; Timmons and Scanlon 2004; Polastre et al. 2004; Ye et al. 2004]. In addition to providing an executable model (in the form of the protocol's TinyOS implementation), Polastre et al. [2004] provide closed-form analytic equations capturing the energy and delay properties of their proposed MAC protocol (**D3S21C11M1**). For example, Polastre et al. [2004] model the energy consumption of a system employing their MAC implementation, E, as a function of the energy spent in receiving communications, E_{rx}, for transmissions, E_{tx}, for idle listening, E_{listen}, sensor access, E_d and sleeping, E_{sleep}:

$$E = E_{rx} + E_{tx} + E_{listen} + E_d + E_{sleep}.$$

E_{tx} and E_{rx}, depend on the MAC implementation, and, for example, E_{tx} is defined in terms of the sampling rate, r, of the application which uses the MAC layer for communication, the MAC layer's configured preamble length, $L_{preamble}$, packet size, L_{packet}, the time to transmit a unit of data in the packet or preamble, t_{txb}, the radio subsystem's current draw during transmission, c_{txb}, and the system's operating voltage, V:

$$E_{tx} = r(L_{preamble} + L_{packet})t_{txb}(c_{txb})V.$$

Other examples of models relating to the MAC layer include those for modeling, e.g., collision probability [Gupta and Kumar 2000].

3.7 Network and transport layer models

At higher layers in the traditional stacking of protocols, the activities of modeling become significantly more complex. This is because the behavior of the systems being modeled (e.g., protocols), become increasingly more dependent on state. It therefore becomes difficult to employ deterministic closed-form models, and modeling activities increasingly turn to behavioral simulation models. Also in increasingly more frequent use (compared to node hardware, PHY and MAC models), are models built from statistical analysis of real system measurements [Cerpa et al. 2005], and stochastic process models, such as Markov models [Chiasserini and Garetto 2004], or other probabilistic [Nurmi 2004; Kunniyur 2005], and queuing-theoretic approaches [Zhao and Delgado-Frias 2006]. Kunniyur [2005] presents techniques purposely designed to circumvent the complexity of stochastic models such as those based on Markov analysis, and illustrates models relating channel access delay and end-to-end delay, to channel access probability, transmission power, network load and node deployment density.

3.8 Operating system and runtime system models

Models also play a role in evaluating the effectiveness of operating systems for wireless sensor platforms, and have been employed on occasion to evaluate performance under a range of parameter settings [Han et al. 2005]. For example, Han et al. [2005] present closed-form expressions capturing the energy usage of the system as a whole (E_{total}), in the presence of the need to perform dynamic code updates (at cost energy E_{update}), in terms of the power dissipated while a node is active (P_{active}), idle (P_{idle}), asleep (P_{sleep}), the application duty cycle while awake ($DutyCycle$), and the active and idle times, T_{active} and T_{idle}:

$$E_{total} = E_{update} + P_{\text{average}} \cdot T_{\text{live}},$$
$$P_{average} = P_{awake} \cdot DutyCycle + P_{\text{sleep}} \cdot (1 - DutyCycle),$$
$$P_{awake} = P_{active} \cdot \frac{T_{active}}{T_{active} + T_{idle}} + P_{idle} \cdot \frac{T_{idle}}{T_{active} + T_{idle}}.$$

This model, which falls under the classification **D6S21C11M5**, aids in the comparison of the utility of facilities in their operating system (low-overhead dynamic code updates/loading), to other platforms lacking those facilities.

3.9 Application models

Most of the applications typically deployed in wireless sensor networks may be considered in terms of a small set of core algorithms or *kernels*:

—**Spatial mapping:** here, the objective is to determine the intensity of some phenomenon across a geographic region.

—**Object tracking:** this involves the use of a network of nodes to track the location and motion of an object that is possibly not part of the network.

—**Sensor motion tracking:** in contrast to *object tracking*, the objective here is to determine the trajectory of actual sensor nodes in some geographic region.

—**Data/code dissemination/aggregation:** the objective in this case is to achieve the transfer and aggregation of data or code across an *ad hoc* network of nodes.

In practice, models of applications appearing in the sensor network literature are usually behavioral models, typically constructed as precursors of actual implementations, or derived therefrom. Examples of application models in the literature include the description of a suite of object tracking kernel algorithms in [Fang et al. 2003], models and domain-specific metrics for target tracking applications [Chu et al. 2001; Pattem et al. 2003], and models for the data delivery cost in directed diffusion data aggregation / routing algorithms [Intanagonwiwat et al. 2003].

3.10 Environment, mobility, and deployment models

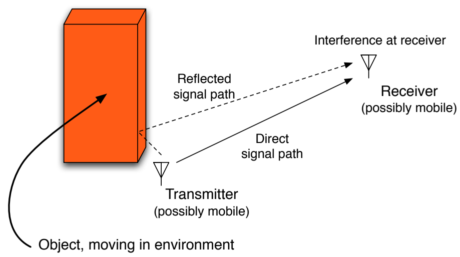
Wireless sensor networks are driven in a large part by the evolution of phenomena in their environments. The environment may be regarded as being composed of a variety of components, ranging from phenomena such as light and sound, which might be monitored by an application, to signals such as stray electromagnetic (EM) radiation, or modulated EM signals resulting from a communication radio transmitter. Models of the environments in which wireless sensor networks are deployed thus capture the manner in which such signals evolve in space, and over time. The contexts in which these models are employed, range from microclimate monitoring, to monitoring the motion of humans in buildings, cars on highways, etc. The importance of the correct modeling of the environment in which a network is deployed has previously been highlighted [Samper et al. 2006]. Samper et al. [2006] demonstrate that realistic global models of phenomena in an environment are likely to generate traffic patterns which are very different from the Poisson arrival processes for events typically assumed in network-only simulations; the environment models they introduce therein, are non-deterministic behavioral models (**D8S12C12M4**) incorporated into a simulation environment.

The motion of objects in an environment affect the structure of the environment. When sensors are themselves in motion, this motion can be seen as a continuous change in the nature of the environment. One can for these reasons consider mobility models alongside environment models. There have been many studies of mobility models in wireless ad hoc networks [Camp et al. 2002; Lin 2004], and many of the conclusions of these studies are relevant to wireless sensor networks. Examples of mobility models in the literature include the *random waypoint model* (in which nodes move in a random manner between a set of waypoints uniformly distributed over a convex area, with (possibly) randomly chosen velocities for motion between each pair of waypoints) [Johnson and Maltz 1996; Bettstetter et al. 2003] and others such as the Gauss-Markov mobility model (in which a node's future path depends on its past path) [Liang and Haas 2003], or even a simple random walk. The importance of realistic mobility models has been pointed out in several studies [Jardosh et al. 2003; Yoon et al. 2003; Yoon et al. 2006].

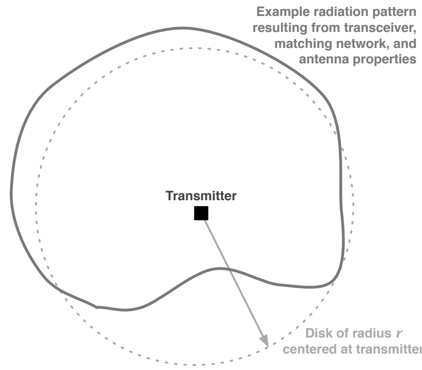
The relation between environment models, mobility models, and channel models, is illustrated in Figure 6(a). The figure shows a simplistic ray-tracing illustration of the path taken by a signal from a transmitter to a receiver within an environment. As the signal from the transmitter is radiated in all directions (Figure 6(b)), it may reflect off objects that are not even in the line-of-sight between the transmitter and receiver. Such reflections lead to multiple signals arriving at the receiver, and these may interfere constructively or destructively due to the time difference of their arrivals, as well as the phase differences that may be induced during reflections. The signal propagation model of the medium should thus ideally capture the manner in which signals travel and are attenuated in space, and the mobility and environment models should likewise capture the objects in the environments of communicating entities, as well as any motion therein. Rao [2007] provides a table of the path loss properties of many materials including metal and concrete, as well as empirical estimates of the path losses between floors of a multi-level building.

Existing studies of environment models for wireless sensor networks range from studies of the spatial correlation of sensor data [Jindal 2004] and the modeling of diffusion phenomena in environments [Rossi et al. 2004], to more general studies of construction of models for noise [Lee et al. 2007] and other sensed phenomena in the environs of sensors [Kansal et al. 2005; Hwang et al. 2007; Hwang et al. 2006], environment modeling tools [Chulsung Park; Chou 2006; Samper et al. 2006], and case studies [Tolle et al. 2005].

The deployment of wireless sensor networks can have a significant effect on their effective operation. It has therefore been of interest to model the placement of nodes in deployments [Toumpis and Gupta 2005; Zhang and Wicker 2004; Krause et al. 2006], the influence of topologies on sensed phenomena, and the intelligent deployment of nodes to maximize connectivity and lifetime [Hou et al. 2005; Ganesan et al. 2004]. A simple concrete example of a deployment model is a uniform random placement of nodes over a given area. Such



(a) Interaction between objects in environment, mobility, and signal propagation.



(b) Illustration of anisotropic nature of signal radiation from a transmitter.

Fig. 6. Environment and mobility models, and their interaction with channel models.

simple models may however have undesirable side effects when employed in simulation studies, such as inaccurate estimates of node degrees in the topology connectivity graph, due to boundary effects at the edges of the simulated area; [Corbett et al. 2006] discuss techniques that address these problems.

3.11 A taxonomy of sensor network modeling research

Table VI lists a number of examples of entries from the wireless sensor network literature with designations of their alignment to the classification system introduced in this survey.

From Table VI, it can be observed that a majority of the models in the sample of papers listed therein incorporate randomness in some form or another; this is to be expected, as the properties of wireless sensor networks are in general difficult to capture with deterministic models. Papers describing multiple models (e.g., both channel models and environment models in the case of [Cavilla et al. 2004]) are listed multiple times, and papers in which the classification in one or more dimensions is either ambiguous or not possible (e.g., the structure/form dimension for [Myers et al. 2007]), have a **0** as the dimension index (no bullets in the table in the corresponding columns). In the table, we have included papers which only describe metrics (e.g., [Ammer and Rabaey 2006; Hao et al. 2004]), and these thus have the classification **0** under all the dimensions except those for the metrics they describe; as described previously, the unspecified dimensions are thus dropped, leading to **M3** (dependability metric) and **M5** (energy metric) classifications.

4. MODELING TOOLS

Models, and the tools employed in their creation and evaluation, go hand-in-hand. Tools for the evaluation of sensor network models range from symbolic and numeric analytic tools such as Mathematica and Matlab, to special purpose simulators and simulation-support libraries. Tools in popular use may be classified as *operating-system-specific* modeling tools

Table VI. A sample classification of 32 research articles describing models and metrics, appearing in the wireless sensor network and related literature in the last decade.

	D									S				C				M					
	Hardware / Circuit-Level Models	Radio / PHY Models	MAC / Link Layer Models	Network Layer Models	Transport Layer Models	OS / Runtime Models	Application Models	Environment/Mobility/Deployment Models	Cross-Layer Models	Closed-Form Analytic	Behavioral	Stochastic	Deterministic	Regression	"First Principles"	Abstract Values	Concrete Values / HW Calibrated	Energy	Timing	Dependability	Spatial Events / Detections	Multi-Metric	
Amm[2006]																		•					M5
Arf[2006]	•									•			•	•		•			•				D1S21C22M2
Bal[2004]									•		•		•		•		•					•	D9S11C11M1
Beh[2007]	•										•		•		•		•	•					D1S11C11M5
Bou[2005]			•							•		•			•		•					•	D3S22C11M1
Cam[2002]								•			•	•			•	•					•		D8S12C12M4
Cav[2004]		•								•			•	•			•			•			D2S21C21M3
Cav[2004]								•		•		•			•		•				•		D8S22C11M4
Cer[2005]				•								•		•			•			•			D4S02C21M3
Chi[2006]								•		•		•			•	•					•		D8S22C12M4
Fan[2003]							•			•		•			•	•					•		D7S22C12M4
Gan[2005]	•									•			•		•	•			•				D1S21C12M2
Han[2005]						•				•			•		•		•	•					D6S21C11M5
Hao[2004]																				•			M3
Hwa[2007]								•			•	•			•	•					•		D8S12C12M4
Ina[2007]		•								•		•			•	•				•			D2S22C12M3
Int[2003]							•			•			•		•	•			•				D7S21C12M2
Jar[2003]								•			•	•			•	•					•		D8S12C12M4
Jin[2004]								•		•		•		•			•				•		D8S22C21M4
Jun[2005]				•						•		•			•	•			•				D4S22C12M2
Kun[2005]				•						•		•			•	•			•				D4S22C12M2
Lee[2007]		•								•		•		•			•			•			D2S22C21M3
Mye[2007]		•												•			•			•			D2C21M3
Nur[2004]				•						•		•			•	•							D4S22C12
Pol[2004]			•							•			•		•		•					•	D3S21C11M1
Qin[2006]	•									•			•		•		•	•					D1S21C11M5
Rao[2007]		•								•			•		•		•			•			D2S21C11M3
Sal[2006]		•								•		•			•	•				•			D2S22C12M3
Sam[2006]								•			•	•			•	•					•		D8S12C12M4
Wan[2007]	•										•		•	•			•	•					D1S11C21M5
Zho[2006]		•								•		•			•	•				•			D2S22C12M3
Zun[2004b]			•							•		•			•	•				•			D3S22C12M3

(such as TOSSIM [Levis et al. 2003] and PTOSSIM [Shnayder et al. 2004]), *discrete-event simulation libraries and network simulators* (such as Omnet++ [Varga 2001], NS-2 [ISI 2008] and GloMoSim [Zeng et al. 1998]), and *instruction-level simulators* (such as Avrora [Titzer et al. 2005], ATemu [Polley et al. 2004], Worldsens [Fraboulet et al. 2007] and Sunflower [Stanley-Marbell and Marculescu 2007]). Other tools whose use appears in the wireless sensor network literature include Ptolemy [Baldwin et al. 2004], EmPro [Chulsung Park; Chou 2006], SenQ [Varshney et al. 2007] and EmTos [Girod et al. 2004].

The models employed in OS-specific tools such as TOSSIM and PTOSSIM are by definition specific to the simulation of applications for only one operating system (in this case, TinyOS [Hill et al. 2000]), and are rarely reusable or generalizable to other system software platforms. In the case of TOSSIM and PTOSSIM, the models are executable behavioral models, typically the same code that is compiled for execution on real hardware. In simulation, the properties of the entire system are modeled by the tools, which emulate the presence of the operating system. These models may thus be seen as cross-layer, multi-metric models, encapsulating everything from the application, down through the network protocol stack to the hardware (**D9S11C10M1**).

In contrast to OS-specific simulators, which implicitly model most aspects of a system and the environment in which it executes, discrete-event simulators such as Omnet++ typically provide little or no built-in support for modeling aspects of a system other than the exchange of messages between communicating entities—no built-in modeling of the environment of a node, of its computation, wireless communication channels, power consumption, or batteries for that matter. What Omnet++ does provide is a notion of nodes comprising a network, events that these nodes may send and receive, and tools for gathering information and statistics on the evolution of the nodes over time. Users modeling a wireless network in Omnet++ must thus construct their own models for a wireless channel (e.g., modeling path loss and inducing bit errors in modeled communicated messages). Extensions of the Omnet++ simulation library, such as the *INET Framework* and the *Mobility Framework* provide more integrated support for modeling various aspects of mobile and fixed networks. Although the Mobility Framework was developed primarily for studying mobile ad hoc networks, it provides an infrastructure for the layering of protocol models that may be used when modeling networks from other application domains, such as when modeling wireless sensor networks.

Different tools are suited for different tasks, and yield different tradeoffs between the accuracy of quantities being modeled, simulation speed, and the effort required to setup simulation or modeling activities. While instruction-level simulation tools provide low-level timing information, and may also enable more accurate estimation of power dissipation of both compute and communication resources, they are typically slower than network-level simulators. On the other hand, although network-level simulators may be faster, they require the explicit accounting for application behaviors that are abstracted away at the network layer, such as the necessary delays in computation, communication patterns driven by sensing events, and so on—all of which occur as a result of actual application code, in real hardware deployments as well as in instruction-level simulators.

5. CHALLENGES AND FUTURE DIRECTIONS

This survey paper presented a coherent organization of a large collection of existing models in a taxonomy of wireless sensor network models. In addition to serving as a collection and organization of the body of knowledge pertaining to models and their applications in sensor networks, the taxonomy provides some insight into the distribution of types of available models, and current directions in the use of models in sensor network research. It enables researchers interested in models of a given type, e.g., energy models of network-layer properties, expressed as deterministic behavioral models, constructed by regression analysis, and based on actual system measurements or characterization data, to quickly lookup examples of such models—in this case, models under the classification **D4S11C21M5**. The notation introduced in this survey permits significantly more succinct descriptions of types of models.

Every survey paper of limited length will necessarily not be able to include all relevant literature on the topic being surveyed, and will furthermore become outdated with time. We have tried to include as many representative entries from the recent research literature as possible in the survey. To accompany the survey, we have created an online resource, available at `http://taxonomy.sflr.org`, cataloging all the models referenced, with facilities for easily adding new entries. For example, to obtain a description of the model category **D4S11C21M5**, researchers can access the URL `http://taxonomy.sflr.org/v0/D4S11C21M1`, to obtain a list of currently known models of this type, links to research papers describing the models, and bibliographic entries for citation. The online resource also enables the research community to comment on entries in the catalog, as well as to suggest new entries. We have included a version number in the access URL to enable future revisions of the classification system, while maintaining existing entries. The version described in this survey is designated *version 0*, as evident from the `v0` prefix in the previous URL.

There is much work yet to be done, and many challenges yet to be addressed in the area of models for wireless sensor networks. Among these challenges is the need for a consensus on, or a *de facto* standard format for, models of the various forms surveyed. In the current state of affairs, there is a diverse set of tools employed even for models of the same type, modeling the same metrics, and this makes it difficult to perform reasonable comparisons between research results. For example, an agreement on a preferred tool (and its associated format) for constructing closed-form analytic models, along with an agreed set of parameters and evaluation metrics (if possible), will aid the interchange of models, and comparisons of published models. The taxonomy presented in this paper may serve as a guide to such directions.

Another interesting challenge facing modeling activities in wireless sensor networks, is the integration of models of various structural forms, e.g., executable models with analytic models, within a larger modeling framework. This is not in itself a complicated task; the challenge lies in being able to define and to *implement* a framework for the interconnection of models of such different structural forms (possibly following the conventions of the ideas proposed earlier in this section), from different sources / research groups. Other challenges include ensuring accuracy of predictions made from the composition of models (through validation against real systems), and the construction of cross-layer models such as those illustrated in Section 2.3.

The future of models and their application in wireless sensor network research looks promising. In the best of all possible worlds, we would hope that developments in the direction of ideas presented above, and utilizing the classification system presented in this survey, will enable the easy and frequent exchange of models between researchers, and the validation of models of various types, capturing the properties of various aspects of sensor networks.

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