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MINIATURIZED INSTRUMENTATION FOR FIELD APPLICATIONS: GENERAL CONSIDERATIONS FOR ENVIRONMENTAL SENSOR NETWORKS

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Various aspects of chemical instrument miniaturizing are explored. The limitations imposed by scaling laws are discussed, and the influences of system dynamics on chemical and physical behaviour of molecules in microsystems are presented. The complexity of chemical systems, as defined by intra- and intermolecular forces, influencing minimum device dimensions is illustrated for solution and gas-phase species. The basic concepts for environmental sensor networks are presented for a hypothetical system.

Keywords: Environmental sensor networks; Miniaturization; Detection limits

INTRODUCTION

The futuristic concept of miniaturization projected by popular media provides for a utopian backdrop where sub-microscopic devices, machines and instruments perform a variety of complex tasks. This generalized concept is clearly an extension of what has been experienced in electronic industries. According to Moore's law [1], the number of transistors per unit area on a processor is doubled roughly every year (this growth pace has been adjusted to every 18 months since 1970). The implications of Moore's law for consumer electronics and computational devices are far-reaching, allowing for progressively smaller and more powerful devices. Clearly, when it comes to miniaturization, the field of electronics has experienced astonishing progress during the past four decades.

More recently, physical scientists have been working toward reducing the size of typical laboratory analytical instrumentation to facilitate environmental, field, process and clinical analysis. Miniaturization of laboratory equipment, however, significantly lags behind the electronics industry. In chemistry, miniaturization holds great potentials for high-throughput synthesis and rapid analysis, and it offers a large reduction in reagent chemicals and resultant waste streams [2]. One consideration that is often

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missing in comparison of electronic with chemical systems miniaturization is the contrast in scaling laws and how they differ in these two systems. The general notion for chemical miniaturization is that reducing the system dimension sizes from 1 mm to 1 μm should not change the chemistry itself, because the molecules are much smaller than this size regime [3]. Unfortunately, this is not true for many systems, as one has to consider not only molecular dimensions but also intermolecular and intramolecular forces. Furthermore, substantial systematic changes occur in physical properties of matter when transitioning from bulk to meso-phase and finally to nanomaterials. This dependence of physical properties on structural scale of material can be observed even in noble metals. For example, the boiling point for gold clusters a few nanometres in diameter is 600°C less than that of bulk gold [4]. Consequently, when designing miniaturized chemical systems, one has to consider both the potential gain from reduction in size and possible pitfalls associated with chemical dynamics in restricted spatial dimensions. Ultimately, for a miniaturized system to succeed in a commercial arena, one has to strike a balance between flexibility, convenience, size, sensitivity, detection limit, operational needs and overall cost. Several commercial success stories for miniaturized systems have been highlighted in a recent paper by Kopf-Sill [5].

An intriguing application of miniaturization in chemistry is in the chemical synthesis arena. The use of microreactors for organic synthesis can have a major impact on future industrial approaches for manufacturing. When using microreactors (micrometre-dimension channels etched into glass, plastics, or silicon), it is possible to enhance the production capability by combining product purification and synthesis in one device. Microreactors are active chemical synthesis devices in which the channels are used to pump reagents and deliver products to the desired destination. They should not be confused with simple lithographic nanovials that are used for parallel combinatorial chemistry [6]. Because of the smaller sizes of these devices, thermal and mass transfer are enhanced such that the kinetics of reactions are often favourable toward the formation of useful products. An unexpected consequence of using microreactors is the potential increase in chemical yields. Haswell and coworkers have shown that for the synthesis of 4-cynaobiphenyl, they were able to consistently obtain a sixfold increase in product yield when using microreactors instead of normal bulk reactors [7]. Several review articles have described the overall utility and potential impacts for these microreactors [8–10]. Despite their many benefits, however, one should bear in mind that massively parallel systems are required for industrial-scale production.

The future of environmental analysis will be based on networks of small and relatively inexpensive instruments working synchronously to provide accurate and reliable data on specific species of interest. Environmental network sensors will combine several electronic and chemical functionalities that will allow these devices to operate autonomously. Most environmental analysis requires some type of chemical processing (e.g. digestion, purification, derivatization, etc.), which has to be implemented within the desired microinstrumentation. Therefore, the applicability of sensor networks is ultimately tied to the success in developing robust microfluidic and separation systems to handle reagents and analysis in a consistent manner. This is not an insurmountable task, as many microfluidic systems are routinely used for clinical and bioanalytical applications [11–14]. The function of current microfluidic systems ranges from sample handling [15] to protein sequencing [16]. However, chip-based separation on monolithic systems is relatively mature, but further

developments are needed. Gas-chromatographic separation on microdevices is perhaps the oldest example of chip-based miniaturization in analytical chemistry [17]. Other successful chip-based microseparation techniques include various forms of electrophoresis [18,19], electrochromatography [20,21] and ion-exchange chromatography [22].

This manuscript focuses on general aspects of device miniaturization for autonomous sensors and potential applications in environmental analysis. Considering the enormity of different expertise needed to bring an autonomous sensor network into the realm of reality, our goal is to highlight the importance of various elements and their level of current maturity.

DIMENSIONAL SCALES

Current popularity of nanotechnology has driven many exuberant researchers to declare most aspects of miniaturization as *nanotechnology*. One common question with regard to nano- and micro-labels is whether the prefix is used to describe the sample or the device. The term *microanalytical* may imply a large instrument analysing a few microlitres of sample with trace concentration of analytes (e.g. graphite furnace atomic absorption spectrometry), or small systems analysing a sample with a relatively high concentration of analytes (e.g. capillary electrophoresis). Commonly, the term *microanalytical technique* is used for methodologies dealing with micro-sample sizes, and *microanalytical instrumentation* is reserved for devices with small size dimensions. For a device to earn the micro- or nano-prefix, at least one dimension of the instrument must fit within this scale. For example, a cylindrical 1-cm-long capillary with an internal diameter of 1 mm has a total volume of 7.9 μL , and a 1-m-long capillary with 10- μm internal diameter has a total volume 79 nL. Therefore, depending on the specific mode of implementation and imagination of individual authors, either of these systems may be described as normal, micro- or nano-devices.

Comparison of detection limits, as defined by various concentration units, often creates considerable confusion when assessing system performance. Investigators often use the concentration units in a term favourable for the lowest SI prefix. Table I outlines different measurement units and corresponding concentrations for three different analytes (assuming 10^6 molecules confined in 125 pL of solution). While the molarity concentration remains the same for all analytes, the absolute mass and weight concentrations are dependent on the molecular weight of the compound. It is not unusual in the literature to encounter weight-based concentrations for compounds with low molar masses, and molarity concentrations for high-molecular-weight compounds.

TABLE I Comparison of different measurement units for 10^6 molecules of biologically active analyte confined in an observation volume of $50 \mu\text{m} \times 50 \mu\text{m} \times 50 \mu\text{m}$ (125 pL)

Analyte	Concentration			
	MW (g/mol)	Absolute mass (fg)	Molarity (nM)	ng/g
Ascorbic acid	176	0.29	13.8	2.3
Cyanocobalamin	1354	2.25	13.8	18.0
Ovalbumin	42 570	70.69	13.8	565.5

SCALING LAW

Electronic circuits can be miniaturized to a very high degree, but the same level of miniaturization is not possible for chemical systems. In electronic circuits and micro-processors, the active species of interest, propagating through conductors, is the electron. The mass of an electron is 9.1×10^{-28} g, and it has a diameter of less than 10^{-15} m. When comparing electron physical dimensions with the most modern technologically possible nanotransistor gate length of 50 nm [23], we note that the size of the gate is at least 50 million times larger than the electron (the projected limit for transistor gate length is about 10 nm). Moreover, the interactions between electrons are only due to coulombic repulsion, and Ohm's law defines the interaction between the electron and the conducting channel. Electrons do not aggregate to form larger clusters, nor do they behave as active sites for other electrons to perform chemical reactions.

For chemical systems, the scaling law is a dynamic concept. For the compounds listed in Table I, the average hydrodynamic radius (i.e. the radius of a sphere generated by the rotating molecule) ranges from about 0.4 nm for ascorbic acid to about 6 nm for ovalbumin. Furthermore, we must consider the dipole, hydrophobic and hydrophilic interactions as well as van der Waals and intramolecular forces. Additionally, the wall effects, in the form of the double layer created as a result of surface zeta potential, must also be taken into account. For systems with a low ionic strength, this phenomenon may be the dominating factor in limiting the device length scale (as the ionic strength increases, the surface double layer decreases). The strength of dipole-dipole interactions is reduced as function of $1/r^3$ (where r is the distance from the molecule). This type of interaction typically falls rapidly to zero; however, for strong dipoles such as ovalbumin with a dipole moment of 250 Debye (water has a dipole moment of 1.87 Debye), it is simple to recognize that relatively large intermolecular distances are needed to minimize interactions (i.e. dilute solutions).

To minimize unwanted device-molecule interactions, the instrument-length scale must be much greater than the molecular size of the analytes. Accordingly, a system tailored for a biomolecule such as ovalbumin will prove adequate for smaller molecules. To minimize analyte-wall interactions, as a first approximation, the device scale should be at least 10^3 – 10^4 times larger than the analyte scale (e.g. for ovalbumin, fluidic channel dimensions should not be smaller than 12 μ m). For a more accurate answer, one must consider the ratio of active surface area to volume as well.

The scaling issue is not unique to solution chemistry. Previous work for miniaturization of ion-mobility spectrometers has illustrated similar limitations due to space-charge effects [24,25]. Today, the smallest useful ion-mobility spectrometer has an internal drift tube diameter of about 1 mm. It is interesting to note that the smallest instrument scale (1 mm) is about 5×10^6 times greater than the molecular dimensions of the analytes (CH_3I and NO) used to evaluate the system. The space-charge effects remain the limiting factor for miniaturization of mass spectrometers as well.

The influence of scaling laws for miniaturization of analytical systems is most apparent in plasma-based analytical systems. Although several investigators have reported miniaturization of traditional plasmas by confining gaseous discharges within a micrometre-length scale, the inherent properties of these plasmas are significantly changed, and their original function (complete atomization and ionization of analytes) is not preserved [26–28]. Several parameters, such as ion-neutral collision frequency and number densities, are used to unequivocally define the nature of plasmas.

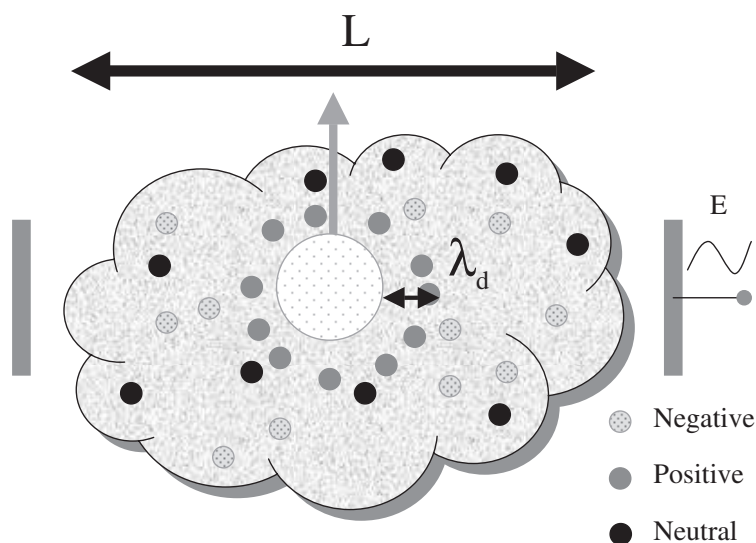


FIGURE 1 Plasma-length scale and the internal Debye shielding distance. By definition, in plasmas the length, L , must be much greater than the Debye distance (λ_d).

Yet, the limitation for plasma miniaturization arises from the fundamental definition of internal plasma-length scales (comparison of plasma length vs. Debye length) [29]:

$$\lambda_d = (KT_e/4\pi ne^2)^{1/2}$$

where λ_d is the Debye length in plasmas, T_e is the plasma electron temperature, K is the Boltzmann constant, n is the plasma number density, and e is the charge on the electron. In physical terms, the Debye length is the layer thickness of charged species that shield an externally introduced perturbing charge. The significance of various length scales for plasmas is shown in Fig. 1. One parameter that must be considered in any miniaturization attempt is the confined plasma dimensions as compared with the Debye length ($L \gg \lambda_d$). For example, typical Debye lengths for analytical plasmas ranging in diversity from inductively coupled plasmas (high temperature, atmospheric pressure) to glow discharges (low temperature, low pressures) are 0.1–0.3 mm. Therefore, the energetics of discharges confined to micrometre lengths are not the same as with plasmas. These discharges maybe used for fragmentation of molecules, but not for atomic spectrometry of real samples [30]. According to the above equation, for a system to have a very short Debye length, it must have a high number density (i.e. high pressure and low electron temperature). The only example of this type of plasma is atmospheric pressure glow discharge, which has been successfully implemented on a monolithic substrate by Manz and coworkers [31]. It is interesting to note that for atomic spectroscopic detection, absorption techniques are best suited for miniaturization, as they are not limited by plasma dynamics and restricted length scale.

DETECTION LIMITS

The drive to reduce the overall instrument size and at the same time minimizing the analyte–analyte, analyte–surface, and analyte–solvent interactions in a confined space will require a sacrifice in sensitivity. The constraints placed upon detection technology are rather significant in microanalytical systems. Even as traditional laboratory analytical instruments such as organic mass spectrometers and inductively coupled plasma mass spectrometers provide unmatched sensitivity and detection limits, the combination of these instruments as detectors with chip-based sampling technology is counterproductive when contemplating ‘system’ miniaturization. For high-throughput analysis, however, this approach is viable [32].

A significant body of work is dedicated to finding the appropriate detection method for on-chip analysis. One of the most successful analytical techniques amenable to miniaturization is electrochemical measurement [33,34]. Electrochemistry is particularly ideal when considering miniaturization, due to a high sensitivity, low power consumption, and typically low costs. Another promising on-chip detection technology is surface plasmon resonance, where extremely low detection limits for specific biological samples have been demonstrated [35]. As expected, optical techniques including imaging, fluorescence and absorption spectroscopy are a major area of miniature detector development efforts [36–38].

When evaluating the required instrumental sensitivity for environmental applications, one must remember that systems will be left in the field, largely unattended. If lab-on-a-chip technology is used, the systems must be robust with adequate detection limits. Adequate detection limits does not imply ultra-trace measurements, and as such, detection technology that best suits a particular applications should be selected for the miniaturized platform.

Representative sample collection presents further challenges to miniaturized instrumentation, especially those that are classified as microanalytical techniques. Many traditional laboratory instrumentation and techniques (e.g. ICP) achieve some degree of sample averaging, resulting in signal averaging, due to the larger sample size required. Both traditional and microanalytical techniques should perform well with homogenous single-phase sample streams, as might be encountered in drinking-water analysis. However, less homogenous systems, such as waste streams with heavy and variable waste loads, would be more problematic. Sampling considerations are even more critical for biological organism detection and classification devices which are designed to sample air, water, food, etc. The transition from instrumentation development to implementation in a ‘real-world’ method requires careful consideration of sources of sample stream inhomogeneity, including differences among sample components in density, solubility, volatility, and viscosity.

ENVIRONMENTAL SENSOR NETWORKS

The first step toward an environmental sensor network is the availability of small analytical devices that are capable of unattended operation. Within the chemistry community, these devices are known as micro-total analytical systems (μ TAS) [39,40]. By design, a μ TAS must function as a self-contained analytical device capable of processing and analysing samples in a fashion compatible with the required data

quality objectives. The data-quality objective is very important because it determines the type of information needed, the complexity of instrumentation, the frequency of measurement, and any required validation steps.

The following case study is used to illustrate the importance of data-quality objectives and their influence on an analytical measurement. From the consumer and economics point of view, it is imperative to ship unspoiled seafood to the market. One solution is to utilize a complex set of analytical tools (GC, NIR, MS, etc.) to determine the concentration of by-products generated due to spoilage. Clearly, implementation of these devices within an autonomous sensor is not trivial. Furthermore, the resulting information must be processed and checked against libraries to ensure adequacy of the seafood in question for public consumption. Alternatively, as demonstrated by McAteer *et al.* [41], it is possible to use a simple temperature data logger to ensure that the temperature of the fish remained low during shipping and transport. By knowing the temperature during the shipping, one can determine whether the fish was exposed to sufficiently high temperatures that allow for spoilage. The data-quality objective was simply to ensure that the public does not consume spoiled fish. While both instrumental methods and temperature logging are fully acceptable methods for obtaining the required data-quality objectives, one is significantly more robust and easier to implement.

From the single sensor point of view, the requirements for autonomous environmental monitoring have been described by Sequeira *et al.* [42]. Spectrophotometric and colorimetric measurements, using well-established reagent chemistry, have found a new popularity in μ TAS systems. The flexibility of reagent analytical chemistry seems particularly suitable for designing miniature analytical systems. Once again, considering the ultimate data-quality objectives, it is not always essential for these systems to be extremely sensitive and have ultra-low detection limits.

The second step toward developing an environmental sensor network is the availability of small electronic platforms that can control the analytical instrumentation and communicate the results back to a central location. Perhaps the most significant breakthrough for network-based environmental analysis has been the development and rapid progress in designing and fabricating functional 'smart dusts' [43]. Smart dusts are microfabricated sensor platforms with a fully integrated 8-bit computer, communication tools and networking capability. These devices are designed to occupy a volume of less 0.03 mL. When combined with a chemical sensing element, smart dusts can perform autonomous chemical measurements. Currently, these devices are designed to measure temperature and light, but all the appropriate circuitry is imbedded for any sensor implementation. The combination of these devices with μ TAS will allow for an unprecedented level of information and communication for environmental analysis. The ultimate goal will be to distribute many different unobtrusive sensors within the environment and then use the ensemble results to model and predict environmentally important occurrences. Because the sensors are small, inexpensive and simple, if one fails, then others within the network will maintain an adequate coverage. Sensors of different type may be co-located to deliver a more complex set of data for specific sensor grid.

The last hurdle toward a fully autonomous sensor grid is the communication network. At first glance, one would suspect that with thousands of sensors in a network: (1) it would be difficult to keep track of each sensor; (2) the amount of data would be simply too enormous; and (3) the lack of communication infrastructure would

limit the sensor utility. Fortunately, many of these problems have been resolved. As a society, we already have developed tools that help with large-area network infrastructure and high information density (e.g. daily financial transaction between banks, stock markets and corporations). The best example of multi-node communication network is the global use of mobile telephones and the resultant worldwide connectivity. At any given time, the authors can use their mobile telephone to call anyone, anywhere, who has access to another mobile phone. The total number of mobile phones in the USA, Asia and Europe exceeds 426 million units [44]. Every operational mobile telephone constantly communicates with a cell-phone tower, declaring its current status. The total number of mobile phones is incredibly large, but each mobile phone node is kept in check by the local area cells. For environmental networks, the same concept can be applied in that the mobile phone infrastructure may be used to communicate pertinent information, especially since the data bandwidth requirements for simple sensors are much smaller than the bandwidth for telephone conversations. For areas that lack adequate mobile-phone coverage, each sensor node can be used as the relay station for another sensor to 'hop' the information to a main communication station. The networking, communication, and data-handling challenge for smart dust is being resolved through source-code software residing on the system [45]. The data density is not of great concern when comparing the sensor network with the current infrastructure and experience for weather forecasting and prediction. Every day, millions of data points are communicated from various dispersed ground stations and satellites to central repositories for weather data (National Oceanic and Atmospheric Administration, in US). The data are then entered into computer models, and short-term weather patterns are predicted, based on temperature, wind and barometric pressure measurements. The data from autonomous environmental sensors should be similar in complexity as the weather data.

The combination of smart dust technology and communication firmware with μ TAS devices will enable massively dense sensor networks operating seamlessly with predictive software models to determine environmental conditions. Because the sensors would be abundant, the detection limits do not have to be very low, since a sensor with a lower sensitivity but near a source term would be able to communicate this information across long distances and perform its function as an early-warning device. Other technological advances such as micro-thrusters [46] and micro-decelerators [47] will enable autonomous sensors to move about and select the best vantage point for environmental analysis.

One further consideration is the ultimate fate of distributed sensors. The lure of using microdevices, because they are considered 'green', may in fact pose a new problem of its own. The green aspects of microdevices stem from the fact that they use less material, have low power requirements, and are considerably less expensive than laboratory devices. The high information dividend at low economic costs will drive the demand for sensor technology. As we have seen during the last two decades through rapid electronic progress, desktop computers are becoming obsolete at an alarming rate. Consequently, as we upgrade to newer models, a graveyard of discarded electronics awaits further scientific developments for proper recycling and disposal of the materials used within these systems. Massive sensor networks of tomorrow may need to be fabricated with a designed limited lifetime, using parts that are naturally degradable. This would minimize the waste generated by obsolete units and reduce the overall electromagnetic background chatter from abandoned units.

A CONCEPTUAL NETWORK

For this example, we have selected to evaluate the system elements needed for a radiological sensor, based on colorimetric radiation dosimetry. This is relevant for environmental application where potential radiological contaminations may be found (e.g. near mining operations, processing plants, power plants, etc.). For instance, the radiation dose can be assessed through a colour change in dosimeter dyes. The change in colour intensity is proportional to the net dose received by the indicator. When the dye is incorporated into a polymer, it can be extruded as a stable thin film, which can be placed between a light-emitting diode (LED) and a simple photodiode. The block diagram representation for this system is shown in Fig. 2. The change in dosimeter (i.e. radiation dose received) can be measured as the increased transparency of the polymer substrate. The internal electronic circuitry can convert the optical absorption data to radiation flux, and the information may be stored on-board for later communication. The external surface of the sensor node is composed of photoelectric materials, which converts ambient light to electrical power needed by the device.

These sensors would be distributed in the field (Fig. 3) to establish a sensor network. The information on each sensor is processed, time-integrated, and transferred to the relay station. If the distance between a given sensor and relay station is too long, the rest of the sensors within the grid can act as intermediates. The information will 'hop' from one sensor to the nearest neighbour, allowing for several consecutive hops until the information reaches the receiving unit. Accounting for the technology used in smart dust systems, these radiological nodes would cost less than \$1 each.

CONCLUSIONS

There is little doubt that miniaturized analytical instrumentation will eventually be a part of our daily lives. By the end of this decade, we will have rudimentary microsensors

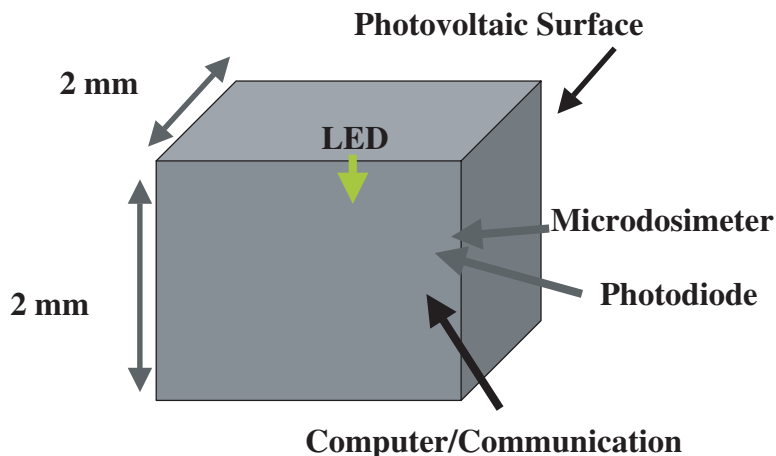


FIGURE 2 Conceptual schematics for a micro-autonomous sensor for radiological measurement.

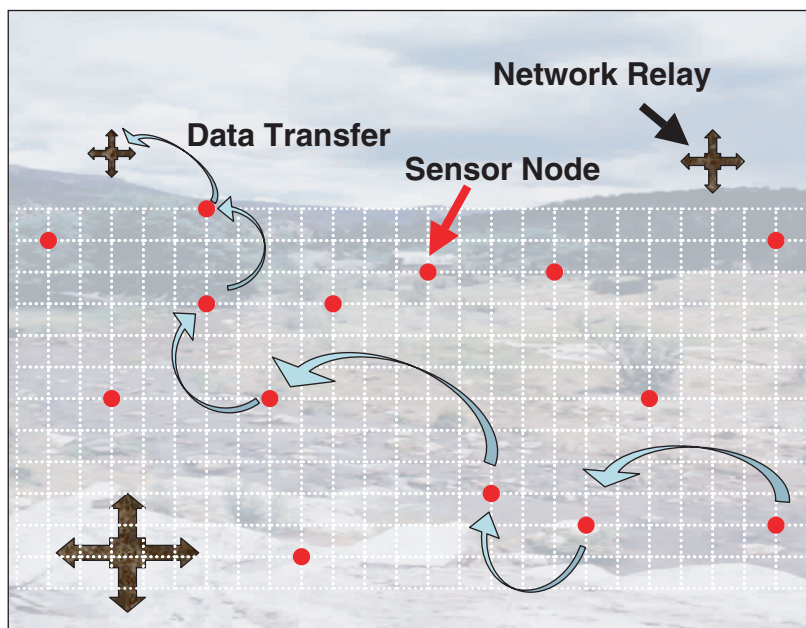


FIGURE 3 Conceptual environmental sensor network. Sensor nodes from a grid network with redundancies can communicate with relays through multiple information hops. The relay stations transfer the network data to a data-processing centre.

with significant computing and communication power incorporated into our routine activities. From smart tags that pay road tolls without stopping the vehicle, to sensor nodes that will determine industrial release of unexpected materials, sensor networks will play a significant role in how large data sets are communicated and processed.

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