Wireless Passive Sensor Networks

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ABSTRACT

The primary challenge in wireless sensor network deployment is the limited network lifetime due to finite-capacity batteries. Hence, the vast majority of research efforts thus far have focused on the development of energy-efficient communication and computing mechanisms for WSNs. In this article a fundamentally different approach and hence completely new WSN paradigm, the wireless passive sensor network, is introduced. The objective of the WPSN is to eliminate the limitation on system lifetime of the WSN. In a WPSN power is externally supplied to the sensor network node via an external RF source. Modulated backscattering is discussed as an alternative communication scheme for WPSNs. The feasibility is investigated along with the open research challenges for reliable communication and networking in WPSNs.

INTRODUCTION

The conventional sensor network communication model assumes the deployment of low-cost, multifunctional sensor nodes operating on limited power capacity of their batteries, which cannot be recharged due to dense and random wireless sensor network (WSN) deployment. Research efforts thus far have sought new methods to prolong the limited lifetime of WSNs through efficient computing and communication techniques [1]. However, the finite-capacity batteries eventually deplete, and the WSN runs out of energy. In conclusion, a battery powered WSN is a disposable system, the use of which is strictly limited by the life span of the batteries.

An alternative source of power, particularly a source without limited capacity, should be considered for WSNs. External radio frequency (RF) power, in this regard, stands as a promising source for WSNs. The problem to be investigated here is whether it is practical to remotely feed the sensor nodes with this new power source.

Considering remote feeding with RF power, RFID emerges as a progressing technology for a number of applications [2]. In passive RFID tags, the whole system is run on the power from an external RF source. The RF power incident on the tag is converted to DC power, which, in turn, operates the internal circuitry of the tag. The tag transmits the information back to the source by modulated backscattering (MB), which is basically modulating the incident RF signal by passively switching the reflection characteristics of the tag [3]. Switching is also accomplished by DC power converted from the incident RF signal. Since no active transmission is involved, the power consumption for communication is very low on passive RFID tags. However, the range of these systems is very short, usually not exceeding 10 m [2].

Passive RFID tags generally transmit stored identification information. In a sensor network, the data obtained by the sensors should be transmitted. The development of wireless, remotely powered telemetry systems [4], in this regard, is an encouraging process. In [4] RF power can be stored on the node and consumed to run a temperature sensor with a transmitter.

In the literature currently there is only one passive sensor implementation with RF transmitters, with which sensors communicate using MB at a range of approximately 15 m indoors, with 5 mW transmission power at a rate of 10 b/s [5]. The implemented system is designed for simultaneous reception of signals that are backscattered from several ultra-low-cost sensors. While there are some preliminary studies that aim to integrate RFID with sensor networks in order to improve sensing capabilities [6], to the best of our knowledge, there has been no effort intended to address the energy limitation problem of WSNs from a fundamentally different approach.

Rather than enhancing the lifetime of the network within the conventional WSN approach, a completely new sensor networking paradigm, wireless passive sensor networks (WPSNs), free of battery lifetime constraint, is introduced in this article. The objective of this work is to investigate the potential of eliminating the lifetime constraint of WSNs and point out the challenges for efficient and reliable communication in WPSNs and related open research issues to the research community. A WPSN is non-disposable, more functional and cost efficient, runs as long as power is delivered in, and remains idle but ready to operate when no power is incident on the network.

The rest of the article is organized as follows. In the next section an overview of the WPSN system model, the communication architecture, and several possible topologies are introduced. We then present the theoretical background of WPSNs. Discussions on alternative communication schemes and protocol related issues for WPSNs are presented in the following section, along with open research challenges. The final section concludes the article.

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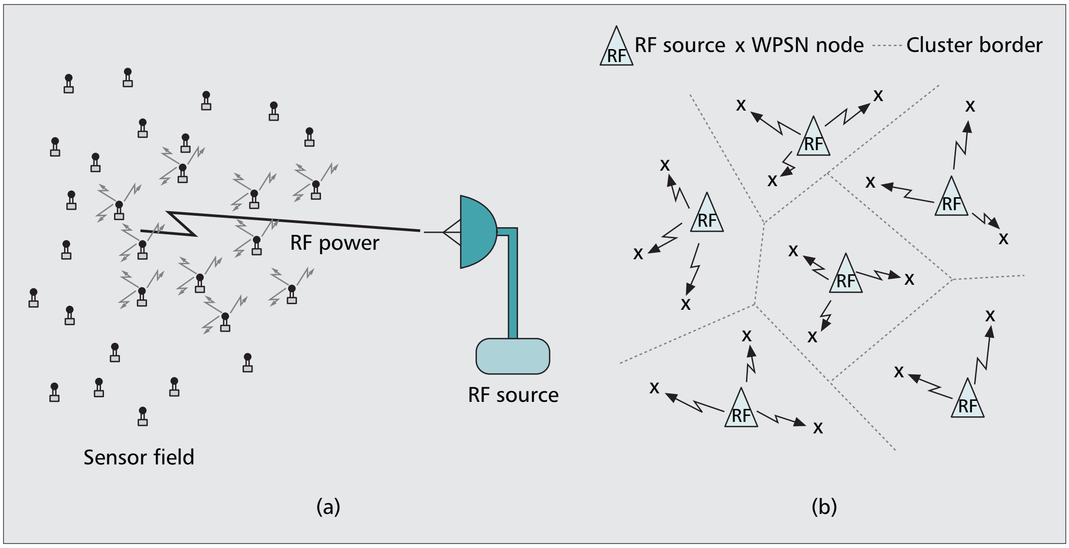


Figure 1. *A typical proposed WPSN topology with passive sensor nodes fed by a) an RF source; b) multiple RF sources in a clustered architecture.*

WPSN TOPOLOGIES AND NODE ARCHITECTURE

Here, possible WPSN topologies are discussed, and a WPSN model is introduced. Moreover, the architecture of a WPSN node and its basic operation in MB are described.

WPSN TOPOLOGIES

Single RF Source — One possible deployment scenario of a WPSN is shown in Fig. 1a. An RF source, which is assumed to have unlimited power, feeds the WPSN nodes with RF power. Voltage is induced on the receivers of the sensor nodes, which is converted to DC. The DC power is either used to wake up and operate the sensor node or kept in a charge capacitor to be used later. The RF source transmits, either continuously or periodically according to the application-specific requirements, RF power to be used by randomly deployed WPSN nodes in sensing, data receiving, and processing. The RF source antenna of WPSN may be either omnidirectional or directional.

Cluster-Based with Multiple RF Sources — An alternative WPSN topology is illustrated in Fig. 1b, where the network is fed by more than one RF source. As explained in the next section, at a specific frequency, the communication range in WPSN depends on the output power used by the RF sources. In fact, the required output power decreases with the number of RF sources as shown in Fig. 2 [7]. Therefore, multiple RF sources increase the communication connectivity in the network [7]. Furthermore, RF sources may transmit at lower output power levels to avoid interference.

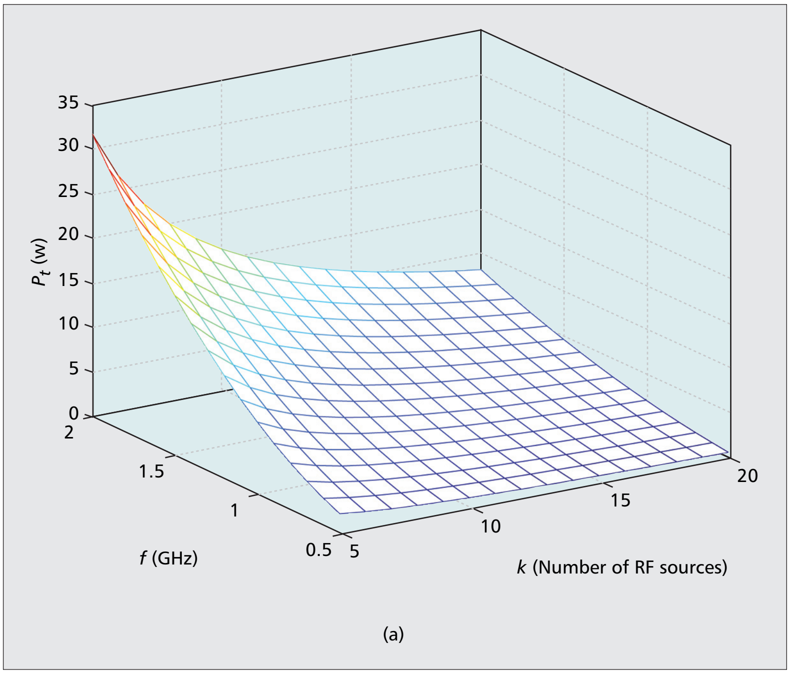
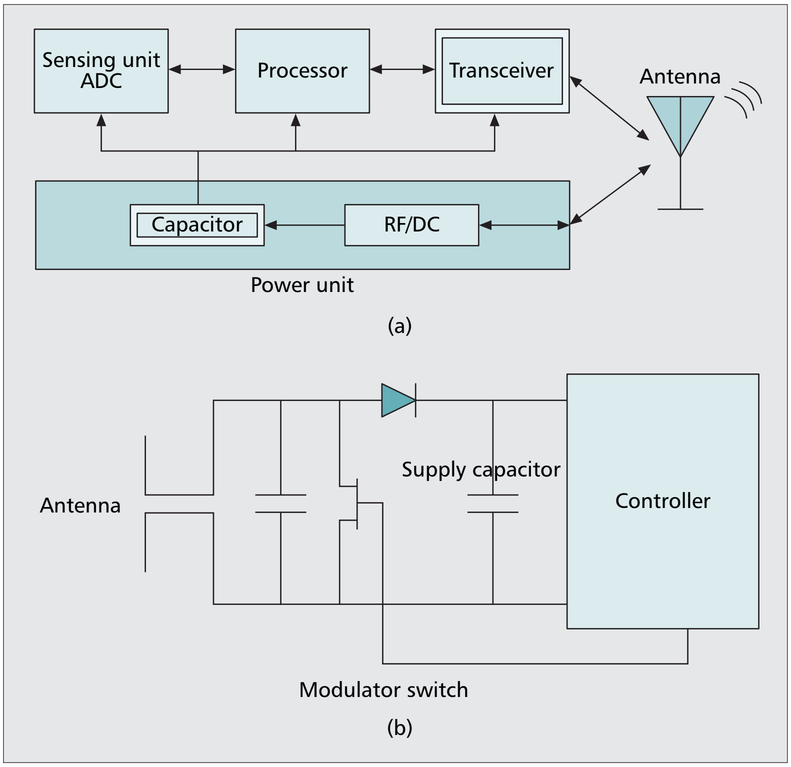


Figure 2. *Required RF output power with the number of RF sources and RF frequency [7].*

Multiple Mobile RF Sources — Another topology similar to Fig. 1b involves multiple mobile RF sources. Adding mobility to RF sources brings certain advantages. According to the event characteristics, some portions of the network may be more active, and hence need more energy. Mobile RF sources provide required power to more active regions with higher priority. Furthermore, communication coverage and connectivity require that all WPSN nodes could sense events and communicate their gathered data. Hence, they should be supplied with the required energy, which makes efficient energy distribution an important issue. Moreover, mobile RF sources with directional antennas can supply WPSN nodes with energy in a fair and efficient manner.

Hybrid Multihop with Active Nodes and Multiple RF Sources — With these topology alternatives, various design choices (e.g., multi-



■ **Figure 3.** *Building blocks of a typical WPSN node and MB circuitry.*

hop data transport and network clustering) can be achieved in WPSNs. Since the operation of WPSNs depends on the energy supplied by RF sources, clustering may be performed by passive or active transmitting nodes as in [8]. Multihop communication may also be possible by either using only passive nodes or adding some active nodes into the network. However, if the network is composed only of passive nodes, the output power or the number of RF sources must suffice to handle continuous energy requirements of clustering and hop-by-hop communication in WPSNs.

WPSN NODE ARCHITECTURE AND OPERATION

Typical WPSN node hardware is shown in Fig. 3a, which deviates from conventional WSN node hardware essentially in the *power unit* and *transceiver*.

In a conventional WSN node, the power unit is a battery. An additional unit called the *power generator* is sometimes offered as a support device to the power unit. It is usually a power scavenging device, such as a solar cell, and is not employed as the sole source of power for the sensor node. In the WPSN node, however, the power generator, which is an RF-to-DC converter, is an inherent part of the power unit and a fundamental device. It is the unique power source of the sensor node. The power unit delivers the power received from the RF-to-DC converter to the rest of the units of the sensor node and stores extra power, whenever available.

The transceiver of a conventional WSN node is typically a short-range RF transceiver. Compared to the other units of the node, the power consumption of the transceiver is considerably high. Hence, here we consider MB [3], a passive and less power consuming method, as the communication architecture for a WPSN. The incident signal from the RF source is reflected back by the WPSN node. The node modulates this reflected signal by changing the impedance of its antenna, thereby transmitting the data gathered from its sensing unit and processed by its *processing unit* back to the RF source, which may also operate as the sink, passively.

The transceiver for MB is much less power consuming and less complex than conventional RF transceivers. Although the receivers for both architectures are quite similar, the transmitter of the MB architecture is basically a switching circuitry for the antenna impedance, as seen in Fig. 3b.

MB technique generates double sideband modulated signals, where data signals are on both sides of the main carrier frequency of the RF source signal. The data switching frequency used in MB is equal to the difference between the frequencies of the main carrier and data signal, which determines the data rate of the WPSN node. Furthermore, the maximum communication range of MB is determined by the intensity of the incident signal and the sensitivity of the corresponding receiver. Thus, long-range communication with a WPSN node is theoretically achievable given a sensitive receiver and a powerful RF source.

Alternatively, conventional RF transceivers may also be employed in WPSN nodes in case sufficient power is available. Hybrid architectures (i.e., MB hardware and RF transceiver operating cooperatively on the WPSN node) may also be considered. Discussions of conceivable communication techniques in WPSNs are provided later.

In our analysis, WPSN nodes are assumed to have low-cost omnidirectional antennas with a nondirectional radiation pattern in the horizontal plane but a directional radiation pattern in the vertical plane, which is advantageous for randomly deployed WPSNs. Hence, a basic omnidirectional and cheap half-wave dipole antenna is considered together with a high gain omnidirectional antenna.

THEORETICAL ANALYSIS OF WPSN

There are two major components of communication in WPSNs:

- RF sources should induce the voltage required for successful operation of passive nodes.
- Data communication should be established between passive nodes, RF sources, and the sink using MB.

POWER INTERCEPTION CHARACTERISTICS OF A WPSN NODE

In a WPSN the RF signal directed on the node supplies all the required power. Thus, it is necessary to see whether a significant amount of power can be transmitted to the nodes over reasonable distances. To estimate the power incident on the nodes, the Friis transmission equation [9] is given by

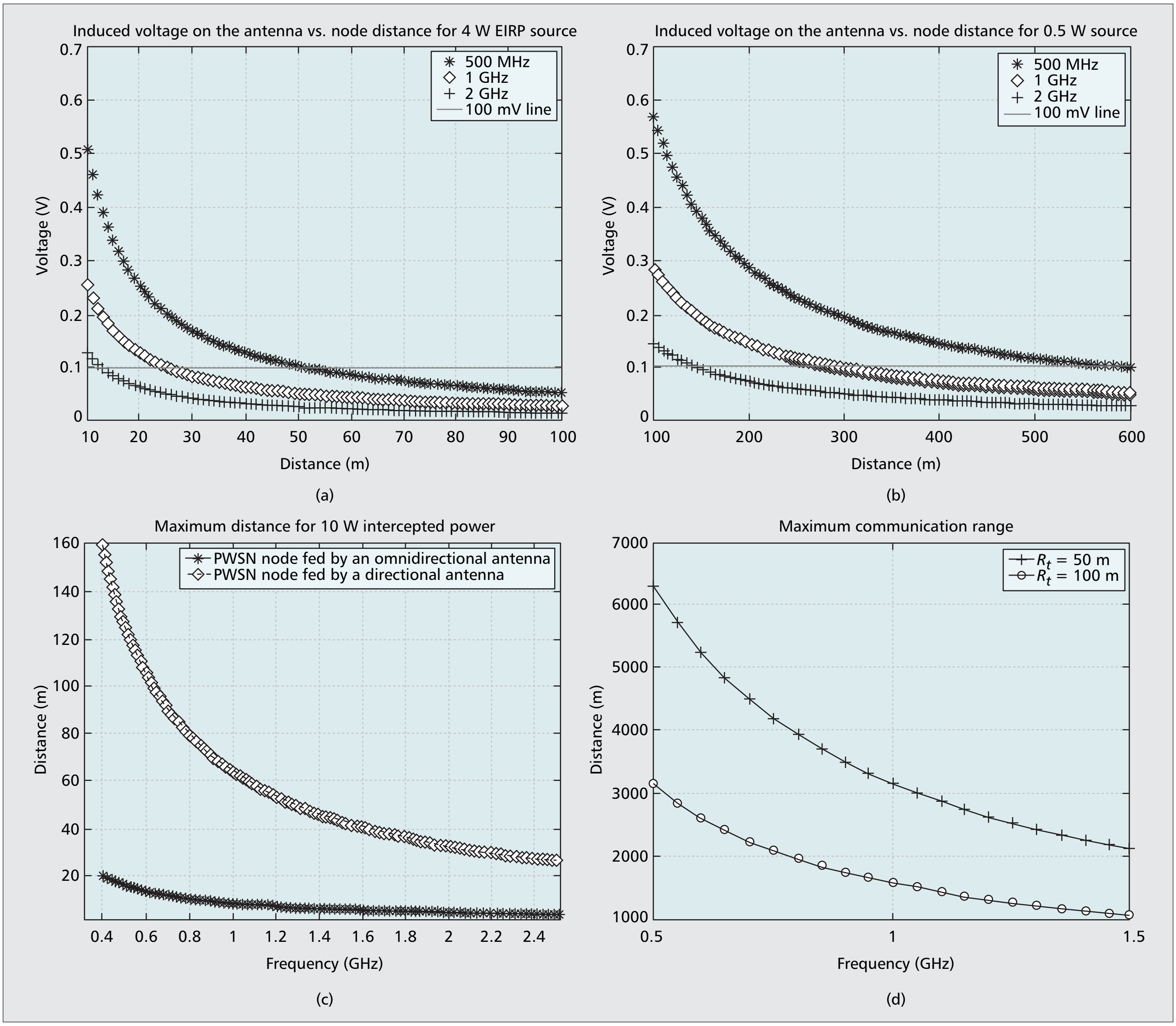


Figure 4. *Induced voltage on the antenna for three different frequencies with: a) 4 W EIRP source; b) 0.5 W source and 30 dBi antenna. Maximum distance c) for 10 mW intercepted power vs. frequency for the node fed by omnidirectional and directional antennas; d) with MB for the half-wave dipole.*

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R}\right)^2 G_t G_r, \tag{1}$$

where P_r is the received signal power, P_t is the power transmitted from the source, G_t is the gain of the transmitting antenna, G_r is the gain of the receiving antenna, λ is the wavelength of the signal, and R is the distance between the antennas.

The read range of simple RFID tags depends on many factors such as the frequency of operation, the power of the reader, and interference from other RF devices. Read ranges vary from 33 cm for low-frequency to more than 1 m for UHF tags [2]. Where longer ranges are needed, such as for tracking railway cars, active tags use batteries to boost read ranges to 100 m or more. WPSN nodes are much more complicated devices than simple RFID tags, and may be used in mission-critical environments such as military applications.

In a WPSN RF signals induce voltage on the node's antenna, and the induced voltage should be rectified to DC in order to be utilized in a WPSN node. Hence, conversion of the intercepted power to DC is a significant issue to be investigated [4]. The receiver converts the RF power to DC as long as 100 mV of voltage is induced on the receiving antenna [4]. Hence, the threshold induced voltage level of 100 mV should be exceeded on the nodes' antenna so that the node may intercept power. The relation between the induced voltage, frequency, and range is expressed by [9] as

$$\frac{G\lambda^2}{4\pi} = \frac{|V_t|^2}{8W_i}\left[\frac{1}{R_r + R_L}\right], \tag{2}$$

where V_t is voltage induced, W_i is incident power density, and R_r and R_L are radiation and load resistances, respectively.

As long as sufficient power to operate all the units of the node can be transmitted, the proposed WPSN nodes may employ conventional active transmitters. Depending on the power intercepted and stored, the nodes may be operated continuously or not.

As seen from Eq. 2, receiver antenna gain is a crucial parameter on power interception characteristics. Higher antenna gain provides better power interception capability. Hence, an 8.5 dBi gain omnidirectional antenna is assumed for WPSN nodes. The radiation and load resistances are 50 Ω.

The emitted power from the source is another effective parameter on the observations. The first constraint is the regulations on effective isotropically radiated power (EIRP). In accordance with this constraint and the directional source antenna assumption, the 4 W maximum EIRP rule of the FCC on WLANs is obeyed. However, for tactical military communications output power levels beyond FCC regulations have been largely used, such as in 100 W tactical radio [10]. Thus, monitoring borders or tactically sensitive areas on an irregular basis can be provided by WPSNs. For such purposes, increasing the EIRP level above the regulations may guarantee the safety of monitoring troops. Regarding such situations, the analysis is repeated for 0.5 W output power with the 30 dBi directional source antenna. Here, note that passive nodes do not transmit similarly high power as their purpose is not to supply power to other nodes. Only the RF sources emit signals with relatively high power.

First, we inspect the conversion of intercepted RF signals to DC. To see the ranges up to which power may be extracted from the incident signal (i.e., the 100mV threshold may be exceeded on the node's antenna), the induced voltage on the antenna vs. distance is calculated by Eq. 2. The initial calculation is made for the 4 W EIRP source case and plotted for three different frequencies in Fig. 4a.

Using Eqs. 1 and 2, the maximum distance to induce 100 mV on the node for 4 W EIRP at 2 GHz is 13 m; this distance increases to 26 m at 1 GHz and 51 m at 500 MHz. Figure 4a reveals that it is possible to transmit operational energy to WPSN nodes while meeting the RF emission regulations. However, the maximum distance of 26 m at 1 GHz claims that the source must come close to the WPSN to transmit power, requiring a 4 W EIRP source to be mobile.

The ranges up to which power may be extracted from the incident signal are also analyzed for high output power (e.g., military) scenarios. Here, 0.5 W output power with the 30 dBi directional source antenna is employed; the corresponding EIRP is 500 W. It is clear in Fig. 4b that 100 mV can be induced on the antenna from 142 m at 2 GHz, 284 m at 1 GHz, and 569 m at 500 MHz, stating the feasibility of WPSNs for military applications (i.e., troops may feed the WPSN from distant secure locations, given high RF power is emitted).

Next, we calculate the maximum distance at which a node can intercept 10 mW power as an approximate value to run the processor and sensor hardware on a typical sensor network node [11]. We initially perform analysis using Eq. 1 for the 4 W EIRP source case. The resulting distance to transmit 10 mW power to the WPSN node at 1 GHz is 1.27 m. This result is anticipated, since the permitted RF power emission levels are expected to limit the power transmission range. Recall the results in Fig. 4a, and note that lower but operational power can be transmitted to the nodes even at these low power levels. The solution to operate a WPSN node is to either store the power or reduce its consumption as discussed below.

For high output power cases, the trade-off between using an omnidirectional antenna and a directional antenna is also observed in Fig. 4c. The omnidirectional source has a gain of 12 dBi, which is a commercially available choice. For the output power level, here, 10 W is used, considering the high emission requirement of power transmission and the safety requirement of the troops who feed the WPSN. In Fig. 4c we observe that at 1 GHz, remote feeding is attainable up to only 8 m for an omnidirectional source antenna and rises to 63.5 m for a directional antenna, which is a significant range improvement. For uniform and practical power delivery, either an omnidirectional antenna with excessive power or a directional antenna fed at reasonable power levels but having extra power consumption to provide antenna rotation or mobility should be used. Here, note that a WPSN with RF sources employing an omnidirectional antenna with high power is also more vulnerable to detection, jamming, and communication interception. Therefore, a moving or rotating directional antenna appears to be a better solution for a WPSN. In any case, from Fig. 4c we may conclude that the power incident on the WPSN nodes is sufficient for reasonable distances.

The converted DC power in the node may or may not be consumed instantly. If it is not to be consumed, the storage of power on the node is of interest. If power storage can be achieved, the WPSN nodes become able to operate, even when the RF source does not feed them. In this regard, the performance of ultracapacitors is very promising due to their increased lifetime, short charging time, and high power density [12, 13]. A 3 V, 10 F ultracapacitor with a time constant of 1.0 s weighs only 6.6 g. For an operation range of 1 V (i.e., 1.5–2.5 V as in [4]) and an average power consumption of 10 mW , a WPSN node with a fully charged ultracapacitor runs about 30 min, although no RF power signal is present. These results claim that a fully charged WPSN node can operate similar to a conventional WSN node for reasonable durations. This option is discussed in detail in the next section.

Consequently, transmission of power through RF signals to a network is theoretically possible. Distances required to transmit and store power (284 m and 63.5 m, respectively, at 1 GHz) are also promising. This conclusion encouragingly implies that a sensor node may be fed by an external RF source, and can store and operate on RF power rather than batteries.

MODULATED BACKSCATTERING

Considering communication by MB, we perform analysis to obtain the maximum ranges over which a source transmits signals and can extract the information carried by the reflected signal it receives. The characteristics of MB are observed by [9]

$$P_r = \frac{P_t G \sigma A_e}{(4\pi)^2 R^4}, \quad (3)$$

where P_r is the received reflected signal power, P_t is the power transmitted from the source, G is the gain of the antenna, σ is the radar cross section of the reflector, A_e is the effective aperture of the receiving antenna, and R is the distance from the source to the reflector. The radar cross section (σ) is a parameter used to characterize the backscattering properties of an object, when it is the target of RF signals. The effective aperture (A_e) of an antenna is the area, which gives the power delivered to the antenna, when multiplied by the incident power density on the antenna itself [9].

In this regard, the ranges at which MB is possible are calculated. We assume the RF source emits 4 W EIRP and has an omnidirectional antenna with 12 dBi gain. A typical receiver sensitivity of the RF source is taken as –100 dBm [9]. The results are shown in Fig. 4d.

The maximum distance of communication at 1 GHZ is around 396 m, which makes MB a practical option for WPSNs. Consequently, it is clear that nodes fed by an external RF source can form an effective WPSN with sufficient coverage. Hence, the results obtained above prove that passive communication is an advantageous method to consider for WPSNs.

COMMUNICATION IN WPSNS

Here, possible transmission techniques and challenges for communication protocols in WPSNs are discussed.

TRANSMISSION APPROACHES

Active Transmission Using RF Power — As long as sufficient power to operate all the units (processing, sensing, and communication) of the node can be transmitted, the proposed WPSN nodes may employ conventional active transmitters. Depending on the power intercepted and stored, the nodes may be operated continuously or not.

Continuous Operation — In this scheme, a WPSN is analogous to a WSN, apart from being powered by RF signals rather than batteries. However, the whole topology should be fed continuously by an omnidirectional antenna. As observed in Fig. 4c, only nodes closer than 4 m to the source may be fed continuously. Hence, such a system may not offer sufficient coverage. For larger coverage, very high power levels are required, which may not be practical for civilian applications due to the RF emission regulations in effect. On the other hand, supplying such high levels of power is a disadvantage for tactical purposes since the high RF power levels amplify the vulnerability to interception.

Discontinuous Operation — WPSN nodes without adequate power to operate continuously may store RF power in a capacitor. This scheme may offer increased coverage, but may fail in time-critical applications. Ultracapacitors enable nodes to operate for considerable durations in the absence of an RF source, making discontinuous operation feasible.

MB for Communication in WPSNs — MB offers another interesting opportunity to WPSN designers. As observed in Fig. 4d, the maximum communication range between a halfwave dipole and an isotropic source emitting 4 W EIRP at 1 GHZ is around 396 m. Power consumption of the node is only due to the resistance switching. Clearly, communication with WPSN nodes at medium and long distances is attainable by MB, and the related power consumption at a WPSN node is considerably lower than that for active transmission. However, this original approach requires thorough investigation and development of a dedicated WPSN communication protocol stack.

Similarly, all WPSN nodes can form a long-distance communication link with a distant user. Hence, any node in a WPSN may possibly act as a sink, providing the data flow from the WPSN to the user. Accordingly, the sink node assignment may be shifted between the nodes, which adds more flexibility and security to the sink-to-user link.

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A mobile RF source is also an option to be considered. A moving source with a directive antenna may feed the nodes in its range and collect information from the event area. Use of a directive antenna increases the maximum source-to-node distance as observed in Fig. 4c. Furthermore, the network becomes less vulnerable to interception as there is no continuous high power level over the sensor field.

Hybrid Methods — There are numerous advantages of MB, as previously observed. At the same time, ultracapacitors enable nodes to operate without RF sources in the vicinity. A combination of both methods (i.e., hybrid architecture) that utilizes the advantages of both architectures might be very useful for WPSNs. Contrary to an MB-only approach, nodes may communicate to the sink even when no RF signal is incident on them. Thus, they may inform the sink about an urgent event and request RF power to resume continuous operation.

PROTOCOL STACK

If active transmission using RF power is chosen as the communication approach, and continuous operation is expected, the operation of WPSN is similar to conventional WSN, except its power source. Thus, existing WSN protocols might be applicable to WPSNs employing active transmission with their nodes operating continuously. Consequently, here we mainly focus on WPSN using active transmission with discontinuous operation, MB, and hybrid communication schemes.

Physical Layer — Due to its unique communication and power circuitry, the physical layer of WPSN should be treated as a completely new design problem.

The advancement of RF power scavenging and storing systems are crucial for realization of WPSNs. Antenna design, signal waveform, and bandwidth should be optimized for maximum

Data centric and flat-architecture protocols offer simple solutions, assuming mostly static or slowly changing network environments. However, node power levels vary in WPSN resulting in a very dynamic environment.

power transmission efficiency. Furthermore, the utilization of transmitted power at the node is a determining factor on the efficiency and lifetime of WPSNs. Power transmission at lower signal levels should be enabled with further improved RF-to-DC converters. Increased storage capacity, decreased charging time, and leakage current of ultracapacitors would also improve the performance and lifetime of WPSNs.

Theoretically, MB is an effective communication method for WPSNs. The transmitter circuitry is extremely simple, but a sensitive receiver is required to receive backscattered signals. The power consumption, size, and complexity of a WPSN receiver should be considerably reduced.

Furthermore, data collected by a WPSN node is brought into the format for transmission in the same way as in conventional sensor nodes. Then the data is transmitted as a bitstream into the captured channel. In this respect, a detailed inspection of the modulation techniques is also necessary in order to simplify the receiver and increase system performance.

Data Link Layer — The data link layer problems of WPSNs deviate from the conventional WSN problems. The WPSN error control mechanism requires thorough investigation. Altering the output power of the transmitter, and hence the signal-to-noise ratio, is one method of error control. However, this method is inapplicable to WPSNs employing MB as a WPSN node cannot alter incident signal intensity. Power control schemes could be considered for WPSN with active transmission as previously discussed. Alternative error control mechanisms such as automatic repeat request (ARQ) and forward error correction (FEC) should be investigated for WPSNs. To be more specific, the retransmission of data may not be practical at the presence of a mobile RF source. The tradeoff between power consumption and added reliability by *FEC-based* schemes should be analyzed. Due to the low power levels of the reflected signals from WPSN nodes, error control coding for WPSNs is tightly related to physical layer issues as well, and needs to be investigated.

Medium access control in WPSNs is also a challenging issue. WPSN nodes share the signals of the RF sources to communicate. Hence, a reservation-based approach such as time-division multiple access (TDMA) may seem advantageous to avoid contention at the RF sources. However, delay may cause problems, especially in time-critical applications [14]. Furthermore, time synchronization is needed, which may be hard to achieve for WPSN nodes.

Lower delay of contention-based protocols makes them preferable for time-critical applications. However, higher collision probability with increasing node density is an inherent problem of these protocols. Moreover, the presence of a high-power RF signal likely to interfere with the reflected signals amplifies the collision problem. Hence, a detailed joint analysis of physical and link layers is needed to attack the collision problem in WPSNs. Finally, hybrid protocols for an effective data link layer in WPSNs must also be investigated.

Network Layer — A number of routing protocols have been proposed to meet the specific network layer requirements of WSNs [1]. Data-centric and flat architecture protocols offer simple solutions, assuming mostly static or slowly changing network environments. However, node power levels vary in WPSNs, resulting in a very dynamic environment.

The cluster hierarchy is inherent in WPSNs if multiple RF sources are employed as in Fig. 1b. Therefore, hierarchical protocols would be an appropriate choice, eliminating the power consumption and delay incurred by the route setup phase.

Location-based protocols require location information of nodes, which is also an open issue for WPSNs. In a WPSN fed by a directive antenna, in fact, there is the information of the node's alignment with respect to a reference point. Therefore, if collaborative processing of these data from all the nodes can be effectively implemented, location-based protocols might suit WPSNs.

Quality of service (QoS)-based protocols generally aim to minimize the energy consumption of a network by using residual energy of nodes as a metric of optimization [1]. This approach has been modified in [15] regarding the power flow into the WSN, which fits into the WPSN network layer design problem. Hence, QoS-based protocols must be explored for routing in WPSNs.

For WPSNs using MB, however, the existence of the RF beam is not just a parameter of power availability, but also an indication of communication capability. Hence, existing approaches should be altered to take the communication capability into account. For active transmission and hybrid cases, existing protocols can be modified so that WPSN nodes demand power in case an event is detected. Finally, to achieve mid- and long-range communication capability in WPSN, multihop routing solutions must be developed.

Transport Layer — The proposed transport protocols for WSNs are all based on active transmission; hence, they are completely inapplicable to WPSNs employing MB and hybrid methods. In WPSNs the transmission of the nodes is highly correlated with the RF beam and the available power at the nodes. The characteristics of congestion in WPSNs differ largely from those of a conventional congestion problem and need to be clearly defined. Then a dedicated mechanism to control the newly defined congestion should be developed.

Similarly, reliable data delivery in WPSNs depends on parameters such as the location of the RF beam and the available power at the nodes. Due to these unique parameters affecting reliability, a new reliability notion in the WPSN environment is also necessary. Finally, effective interaction between these layers and hence cross-layer communication solutions for WPSNs must be investigated.

CONCLUSIONS

In this article we introduce WPSNs, which are theoretically free of energy constraints and have an infinite lifetime. WPSN nodes are powered by external RF sources, and MB is employed for communication in WPSNs. Unique characteristics of WPSNs are presented, and the communication protocol suite for WPSN is discussed along with the open research challenges. Consequently, it is observed that the WPSN is theoretically attainable and stands as a novel approach for sensor network design.

The reliable data delivery in WPSN depends on parameters such as the location of the RF beam and the available power at the nodes. Due to these unique parameters affecting the reliability, a new reliability notion in the WPSN environment is necessary.

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BIOGRAPHIES

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