THE FEASIBILITY, RELIABLE COMMUNICATION AND NETWORKING ASPECTS OF PASSIVE WIRELESS SENSOR NETWORKS

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ABSTRACT

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The primary challenge in wireless sensor network (WSN) deployment is the limited network lifetime due to the finite-capacity batteries. In accordance with this challenge, the vast majority of research efforts thus far have focused on the development of energy-efficient communication and computing mechanisms for WSNs. In this thesis, a fundamentally different approach and hence completely new WSN paradigm, i.e., the Passive Wireless Sensor Network (PWSN), is introduced. The objective of PWSN is to eliminate the limitation on the system lifetime of the WSNs. In PWSN, power is externally supplied to the sensor network node via an external RF source. Hence, the lifetime of the system is no longer determined by the lifetime of the batteries. An alternative communication scheme, modulated backscattering, is also discussed to be utilized in PWSN. The feasibility of the proposed system is investigated along with the open research challenges for reliable communication and networking in PWSN. Additionally, a new medium access schemee for PWSN, Ultra-Wideband PWSN Medium Access Control (UWB PWSN MAC), is presented.

Keywords: Wireless Sensor Networks, Modulated Backscattering, Medium Access Control, Battery-Free Sensor Networks, UWB PWSN MAC

ÖZ

PASİF KABLOSUZ ALGILAYICI AĞLARIN GERÇEKLENEBİLİRLİK, GÜVENİLİR İLETİŞİM VE AĞ KONULARI

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Kablosuz algılayıcı ağları (KAA) gelişimde en büyük zorluk kısıtlı kapasiteye sahip pillerden kaynaklanan sınırlı ağ ömrüdür. Bu zorlukla beraber, bu zamana kadar yapılan araştırmaların büyük çoğunluğu KAA için enerji-etkin haberleşme ve işlem mekanizmaları geliştirmeye odaklanmıştır. Bu tezde, tamamen farklı ve yeni bir KAA yaklaşımı, Pasif Kablosuz Algılayıcı Ağlar (PKAA) sunulmaktadır. PKAA'nın amacı KAA ömründeki sınırlanmayı aşmaktır. PKAA'da güç düğümlere dışarıdan bir RF kaynağı aracılığıyla iletilmektedir. Dolayısıyla, sistem ömrü pillerin ömrü ile sınırlanmamıştır. Alternatif bir iletişim yöntemi, modüle edilmiş yansıtma, PKAA'da kullanılması amacıyla tartışılmıştır. Önerilen sistemin gerçekleştirilebilirliği ile PKAA için güvenilir iletişim ve ağ yapıları konusundaki araştırma konuları incelenmiştir. Ek olarak, PKAA için Ultra Geniş Band PKAA Ortam Erişim Kontrolü (UGB PKAA OEK) adlı yeni bir ortam erişim yöntemi sunulmuştur.

Anahtar Kelimeler: Kablosuz Algılayıcı Ağlar, Modüle Edilmiş Geri Yansıtma, Ortam Erişim Kontrolü, Pilsiz Algılayıcı Ağlar, UGB PKAA OEK

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CHAPTER 1

INTRODUCTION

Conventional sensor network communication model assumes the deployment of low-cost, low-power multifunctional sensor nodes [2]. Among all the design considerations, the power availability is the primary concern which alters WSN design from conventional wireless network design. Conventional wireless network nodes either have infinite power or rechargeable batteries, however WSN nodes run on limited power capacity of their batteries, which cannot be recharged due to dense and random WSN deployment. The research efforts thus far have sought new methods to prolong the limited lifetime of the WSN; either by improvements in the physical layer or by efficient computing and communication techniques [2]. However, the finite capacity batteries eventually deplete, and the WSN runs out of energy.

Clearly, the reason for limited life span is the batteries with limited capacity. Following the depletion of its battery, a sensor node is no longer in service. With the depletion of the batteries of the majority of nodes, the network becomes nonfunctional. After the batteries of the majority of the nodes are depleted, the deployed nodes are inoperable, thus redundant in the environment. 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 WSN. Such a network, i.e., a WSN with unlimited power, is no more a disposable system, hence, more functional and feasible. External radio frequency (RF) power, in this regard, stands as a promising source for WSN. 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, which is about to be utilized in a number of applications [21]. 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 back the information to the source by modulated backscattering, which is basically modulating the incident RF signal by passively switching the reflection characteristics of the tag. The switching is also accomplished by the 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 are very short (e.g. usually not exceeding $10m$) [11, 21].

The passive RFID tags generally transmit the stored identification information. In case of a sensor network, on the other hand, the data obtained by the sensors should de transmitted. The development of wireless, remotely powered telemetry systems [12, 17], in this regard, is an encouraging progress. In [12], RF power can be stored on the node, and then can be consumed to run a temperature sensor with a transmitter.

While there are some preliminary studies which aim to integrate RFID with sensor networks in order to improve the sensing capabilities [3, 11, 18, 20], to the best of our knowledge, there has been no effort which intends to address the energy limitation problem of WSN from a fundamentally different approach.

Rather than enhancing the lifetime of the network within the conventional WSN approach, a completely new sensor networking paradigm, i.e., Passive Wireless Sensor Networks (PWSN), which is free of battery lifetime constraint, is introduced in this thesis. *The objective of this work is to investigate the potential of eliminating the lifetime constraint of wireless sensor networks with PWSN and point out the challenges for efficient and reliable communication in PWSN and related open research issues to the research community.* A WSN without lifetime limitation is no more a disposable system, hence more functional, cost efficient and feasible. The system 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 thesis is organized as follows. In Chapter 2, the overview of the PWSN system model and the communication architecture are introduced. In Chapter 3, the theoretical background of the analysis on PWSN, related derivations and calculations are presented. The discussions on alternative communication schemes are presented in Chapter 4. In Chapter 5, the communication protocol suite for PWSN along with the open research challenges are discussed. In Chapter 6, a new medium access scheme for PWSN, Ultra-Wideband PWSN Medium Access Control (UWB PWSN MAC), is presented. Finally, the thesis is concluded in Section 7.

CHAPTER 2

PWSN MODEL AND COMMUNICATION ARCHITECTURE

Unlike conventional WSNs, the sensor network proposed in this study is fed by an external power source, and is operable as long as power is delivered to the system. In PWSN, the source of energy, as alternative to the batteries of conventional WSNs, is an RF power source. A typical deployment scenario of PWSN is shown in Fig. 2.1.

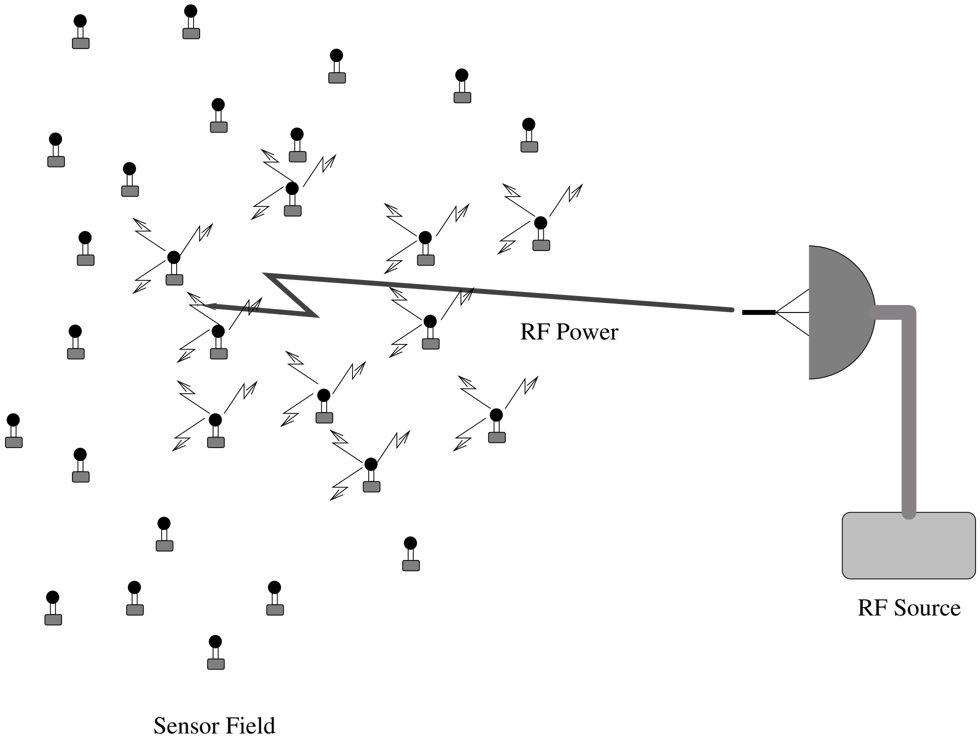

Figure 2.1: A typical proposed PWSN architecture with passive sensor nodes fed by an RF source.

An RF source, which is assumed to have unlimited power, feeds the PWSN nodes with RF power. Accordingly, 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. Like conventional WSNs, the sensor nodes in the system proposed are assumed to be randomly deployed. The RF source transmits[1] RF power to run the sensor network nodes, simultaneously it transmits and receives information from the PWSN nodes. The RF source antenna of PWSN should either be omnidirectional or directional. Omnidirectional antennas assure equal power radiation in all horizontal directions, so that they may feed PWSN homogenously. Directional antennas, on the other hand, have concentrated power radiation in certain directions and are appropriate to feed PWSN from distant locations.

A typical PWSN node hardware is represented in Fig. 2.2. Although it resembles a conventional WSN node at first sight, the PWSN node hardware deviates from the conventional WSN hardware essentially on the *power unit* and the *transceiver*.

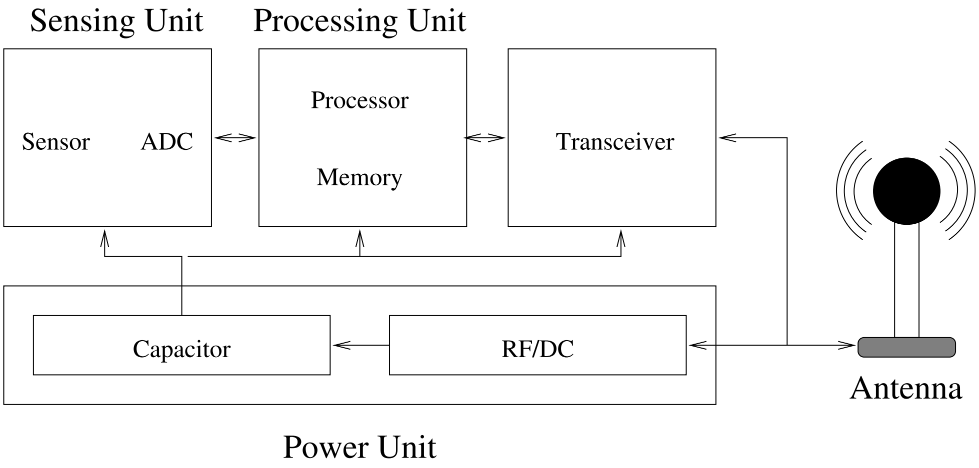

Figure 2.2: Building blocks of a typical PWSN node.

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[1] The RF source may continuously or periodically feed the PWSN according to the system requirements.

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 PWSN node, however, the *power generator*, which is an RF-to-DC converter, is an inherent part of the *power unit* and is 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, on the other hand, is typically a short range RF transceiver. Compared to the other units of the node, the power consumption of the *transceiver* is considerably high. For this reason, here, we consider modulated backscattering [14], a passive and less power consuming method, as the communication architecture for PWSN. In this architecture, the incident signal from the RF source is reflected back by the PWSN node. The node modulates this reflected signal by changing the impedance of its antenna, thereby transmits the data, that is gathered from its *sensing unit* and processed by its *processing unit*, back to the RF source[2] passively.

The *transceiver* for modulated backscattering is much less power consuming and less complex, compared to conventional RF transceivers. Although the receiver for both architectures are quite similar, the transmitter of the modulated backscattering architecture is basically a switching circuitry for the antenna impedance, as seen in Fig. 2.3. Furthermore, the maximum communication range of modulated backscattering is determined by the intensity of the incident signal, and the sensitivity of the corresponding receiver. Thus, long range communication with the PWSN node is theoretically achievable without increasing the power consumption of the node, given a sensitive receiver and a powerful RF source is present.

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[2] The RF source may also operate as the sink in PWSN.

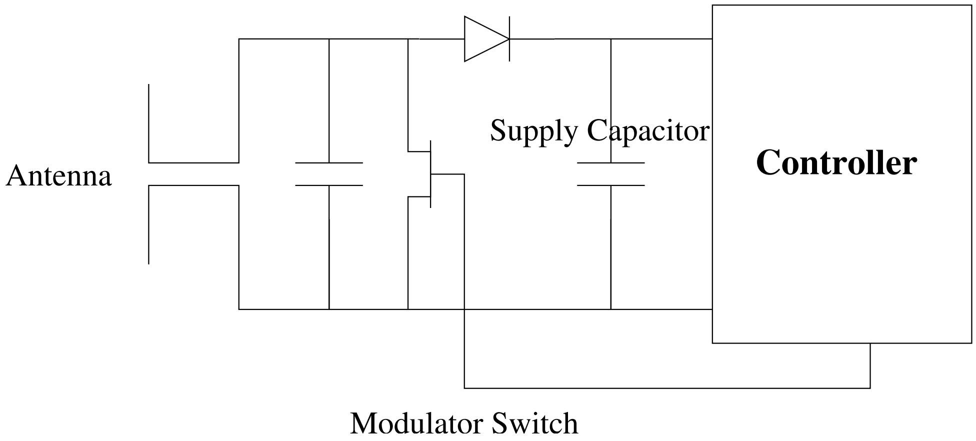

Figure 2.3: Basic modulated backscattering circuitry.

Alternatively, conventional RF transceivers may also be employed in the PWSN nodes [13], in case sufficient power is available on the node. Hybrid architectures, i.e., modulated backscattering hardware and RF transceiver operating cooperatively on the PWSN node may also be considered. Discussions on the conceivable communication techniques in PWSN are provided in Section 4.

In our analysis, PWSN nodes are assumed to be equipped with omnidirectional antennas. The omnidirectional antenna has a nondirectional radiation pattern in the horizontal plane but a directional radiation pattern in the vertical plane, which makes it advantageous for the random deployment assumption of PWSN. To be appropriate for PWSN, the antenna is preferred to be low cost. With these constraints in mind, a basic omnidirectional and cheap half-wave dipole antenna is considered together with a high gain omnidirectional antenna.

Within the PWSN model, we perform analysis to investigate the feasibility of PWSN. The theoretical background, as well as the details and results of the analysis are given next.

CHAPTER 3

THEORETICAL ANALYSIS OF PWSN

In PWSN, the RF signal directed on the node supplies all the required power. Thus, it is necessary to see whether 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 [4] is given by

$$\frac{P_r}{P_t} = (\frac{\lambda}{4\pi R})^2 G_{0t} G_{0r} \tag{3.1}$$

where P_r is the received signal power, P_t is the power transmitted from the source, G_{0t} is the gain of the transmitting antenna, G_{0r} is the gain of the receiving antenna, λ is the wavelength of the signal, and R is the distance between the antennas.

Considering communication by modulated backscattering, 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 modulated backscattering is observed by the radar equation [4]

$$P_r = \frac{P_t G \sigma A_e}{(4\pi)^2 R^4} \tag{3.2}$$

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, which is used to characterize the backscattering properties of an object, when it is target to 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 [4].

In our analysis of modulated backscattering, we assume the gain of the directional RF source antenna as $30dBi$, and the receiver sensitivity of the RF source as $-100dBm$. $30dBi$ is a high gain for a conventional antenna, but it is within reach at an affordable cost. $-100dBm$ is a typical value of receiver sensitivity. Being commonly used, the characteristics of the half-wave dipole, are well known [4]. For the $\lambda/2$ dipole, the radiation resistance is 73Ω, maximum directivity is 1.643, and the radar crossection is approximately 0.86. In this respect, the known radar crossection value makes the half-wave dipole an appropriate choice for the PWSN nodes in the analysis of modulated backscattering. As a result, the half-wave dipole antenna is considered as the PWSN node antenna in modulated backscattering analysis.

In PWSN, RF signals induce voltage on the node's antenna, and the induced voltage should be rectified to DC in order to be utilized in the PWSN node. Hence, conversion of the intercepted power to DC is a significant issue to be investigated. To inspect this problem, the recently developed efficient RF-DC converters may be employed [12]. In [12], the receiver can convert the RF power to DC as long as $100mV$ of voltage is induced on the receiving antenna. Hence, the treshold induced voltage level of $100mV$ should be exceeded on the nodes's antenna, in order that the node may intercept power. In this regard, the induced voltage on the PWSN antenna is calculated by [4]

$$A_{em} = \frac{|V_t|^2}{8W_i}[\frac{1}{R_r + R_L}] \tag{3.3}$$

where A_{em} is the effective aperture of the antenna, V_t is the voltage induced, W_i is the incident power density, R_r is the radiation resistance and R_L is the load resistance. Using (3.3), the relation between the induced voltage and frequency is expressed by

$$\frac{G\lambda^2}{4\pi} = \frac{|V_t|^2}{8W_i}[\frac{1}{R_r + R_L}] \tag{3.4}$$

As seen from (3.4), the gain of the receiver antenna is a crucial parameter on power interception characteristics of the PWSN node. The higher antenna gain provides better power interception capability. As previously discussed, on the other hand, using omnidirectional antennas on the nodes is preferred. Within these constraints, a $8.5dBi$ gain omnidirectional antenna is assumed to be used on PWSN nodes. The

the radiation resistance of this antenna is 50Ω. Antennas with these specifications are available on the market, but the length of these products (i.e around 50*cm.*) form drawback for the randomly scattered tiny PWSN nodes. However, these commercial products are designed for various purposes (i.e marine antennas or outdoor WLAN antennas) antenna design specifically for PWSN can overcome this disadvantage.

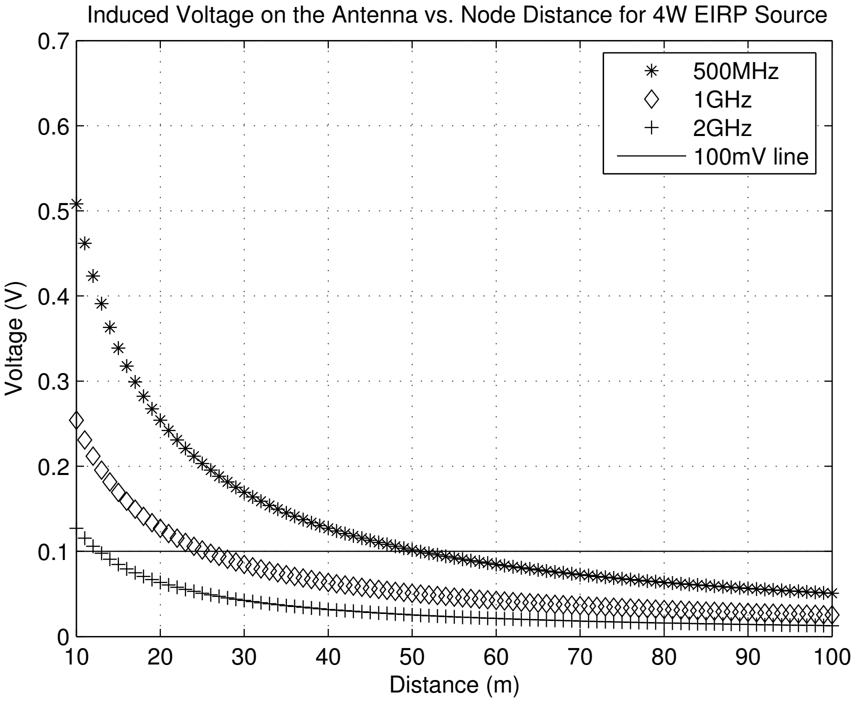

Figure 3.1: Induced voltage on the antenna for 3 different frequencies with a 4*W* EIRP source antenna.

The emitted power from the source is another effective parameter on the observations. The first constraint is of course the regulations on the Effective Isotropic Irradiated Power (EIRP). In accordance with this constraint, and directional source antenna assumption, the 4*W* maximum EIRP rule of FCC on WLAN for directional antennas is obeyed. At this point, the applicability of PWSN on military purposes should be recalled. Monitoring borders or tactically sensitive areas on an irregular basis can be provided by PWSN. For such purposes, increasing the EIRP level above the regulations may guarantee the safety of the monitoring troops. In such scenarios, the

FCC regulations are most likely to be ignored, and the EIRP level is increased to keep the soldiers secure. Regarding such situations, the PWSN feasibility analysis is repeated for $0.5W$ output power with the $30dBi$ directional source antenna.

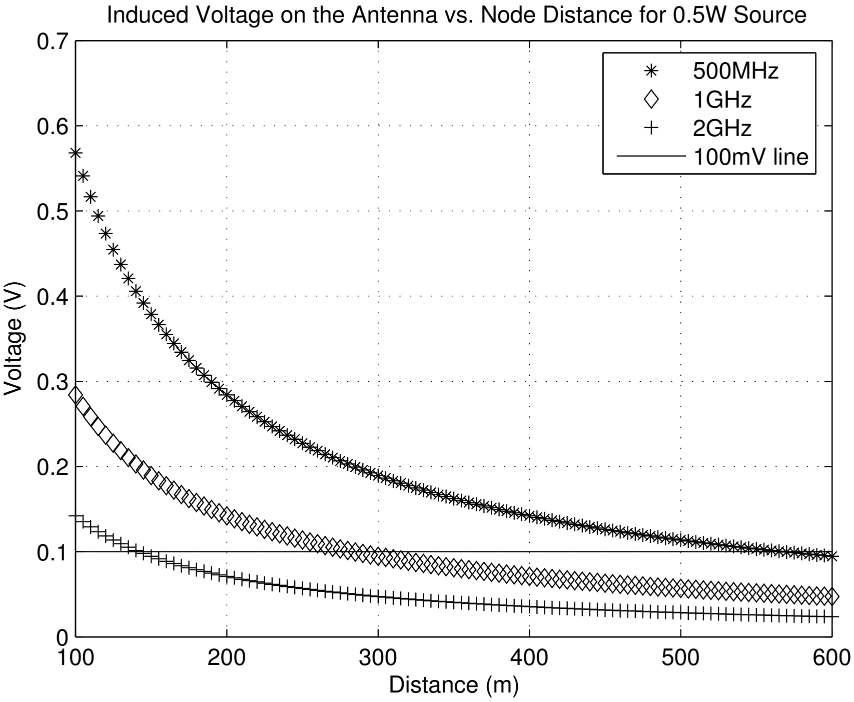

Figure 3.2: Induced voltage on the antenna for 3 different frequencies with a $0.5W$ source and $30dBi$ antenna.

The rest of the analysis is performed in two parts: The details of the investigations on the power interception characteristics are presented in Section 3.1. Then, we discuss modulated backscattering in PWSN in Section 3.2.

3.1 Power Interception Characteristics of the PWSN Node

In the first analysis, 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 $100mV$ treshold may be exceeded on the node's antenna, the induced voltage on the antenna versus distance is calculated by (3.3). The initial calculation is made for the $4W$ EIRP source case and plotted for three different frequencies, which is shown in

Fig. 3.1.

The maximum distance to induce $100mV$ on the node for $4W$ EIRP at $2GHz$ is $13m$, this distance increases to $26m$ at $1GHz$ and $51m$ at $500MHz$. Decreasing range by increasing frequency is expected from (3.4). The conclusion of this plot is that it is possible to transmit operational energy to the PWSN nodes and to meet the RF emission regulations simultaneously. However, the maximum distance of $26m$ at $1GHz$ claims that the source must come close to the PWSN in order to transmit power, requiring $4W$ EIRP source to be mobile.

On the other hand, the same inspection of the ranges up to which power may be extracted from the incident signal is repeated with the high output power, for military application scenarios. Here, $0.5W$ output power with the $30dBi$ directional source antenna is employed, the corresponding EIRP is $500W$. The results are presented in Fig. 3.2.

It is clear in Fig. 3.2 that $100mV$ can be induced on the antenna from $142m$ at $2GHz$, $142m$ at $1GHz$ and $569m$ at $500MHz$ which is a promising result, stating the feasibility of PWSN at high power military applications, i.e. the troops may feed the PWSN from distant secure locations, given high RF power is emitted.

Next, we calculate the maximum distance at which a node can intercept $10mW$ power. Here, it should be noted that $10mW$ is an approximate power value to run the processor and the sensor hardware on a typical sensor network node [9]. We initially perform analysis using the formula (3.1) for the $4W$ EIRP source case. The resulting distance to transmit $10mW$ power to the PWSN node at $1GHz$ is $1.27m$. This result is anticipated, since the permitted RF power emission levels are expected to limit the power transmission range. The results in Fig. 3.1 should here be remembered, and it should be noted that lower but operational power can be transmitted to the nodes even at these low power levels. The solution to operate the PWSN node is either to store the transmitted power or to reduce the power consumption of the PWSN node. These options will be discussed in the following sections.

For the high output power cases, two different RF source antenna assumptions, i.e., first an omnidirectional one, which can feed the surrounding nodes simultaneously, and afterwards a directional antenna are considered. The tradeoff between using an omnidirectional antenna and a directional antenna will be discussed on the results of these calculations, which are shown in Fig. 3.3.

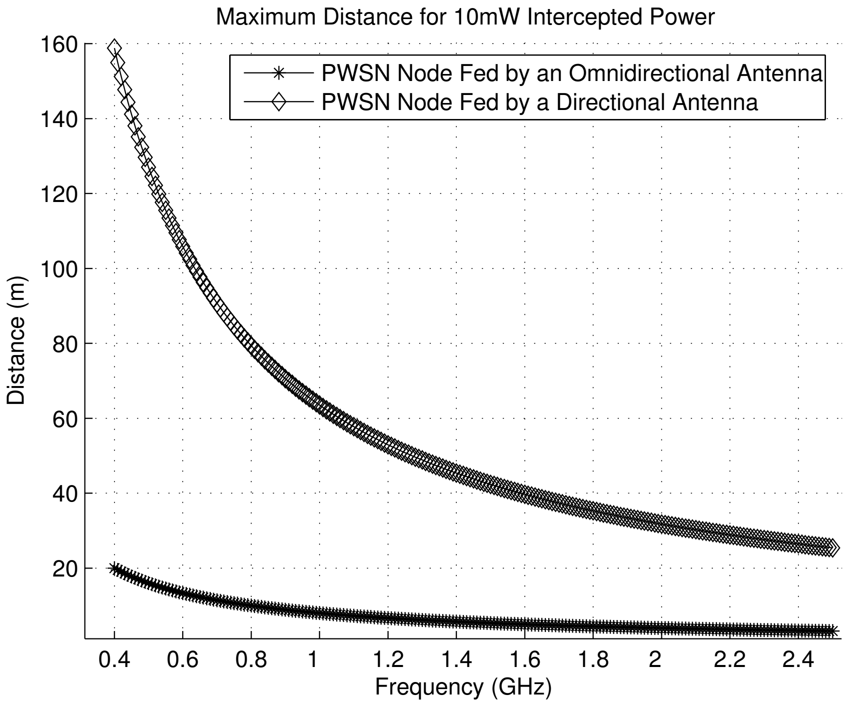

Figure 3.3: Maximum distance for 10mW intercepted power vs. frequency for the node fed by omnidirectional and directional antennas.

The omnidirectional source used in Fig. 3.3 has a gain of $12dBi$, which is a commercially available choice. For the output power level, here, $10W$ is used, considering the high emission requirement of power transmission and the safety requirement of the troops which feed the PWSN. In the figure, we observe that at $1GHz$, remote feeding is attainable up to only $8m$ for an omnidirectional source antenna, but for the directional source antenna the range rises to $63.5m$. The improvement of range by use of a directive antenna is significant. However, the directional antenna transmits power only to a small portion of PWSN, where it is aligned to. A solution to this problem might be a mobile or rotating RF source with a directional antenna. Conversely, a stationary omnidirectional antenna feeds the whole network topology continuously, although with considerably less power. To get equal power levels in the sensor field, either an omnidirectional antenna fed by excessive power or a directional antenna fed at reasonable power levels but having extra power consumption to provide rotation or mobility should be used. Here, it should be noted that the detectability of PWSN is significantly higher, if the omnidirectional antenna is used, due to the constant high power level on the sensor field. Therefore, a moving or rotating directional antenna appears to be a better solution for PWSN. In any case, from Fig. 3.3, we may conclude that the power incident on the PWSN nodes are 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 PWSN nodes become able to operate, even when the RF source does not feed them. In this regard, the performance of the ultracapacitors are very promising [5]. A 3V, 10F ultracapacitor with a time constant of $1.0s$ weighs only $6.6g$. For an operation range of $1V$ (between $1.5V$ and $2.5V$) like in [12], and an average power consumption of $10mW$, a PWSN node with a fully charged ultracapacitor runs about 30 minutes, although no RF power signal is present. These results claim that a fully charged PWSN node can operate similar to a conventional WSN node for reasonable durations. This option will be discussed in detail in Section 4.

Hence, we conclude that, transmission of power through RF signals to the node is theoretically possible. The distances required to transmit and store power ($142m$ and $63.5m$ respectively, at $1GHz$) are also promising. This conclusion encouragingly implies that a sensor node may be fed by an external RF source, can store RF power, and operate on the RF power rather than batteries.

3.2 Modulated Backscattering for PWSN

The transmitted power from the RF source in PWSN may directly be used by the nodes to communicate, namely by modulated backscattering [14]. By this method, the power consumption of the nodes may drop drastically. Thus, the required power level at the nodes decreases and the ranges calculated in Section 3.1 may be improved, increasing the coverage of PWSN without increasing the total power consumption.

In this regard, the ranges at which modulated backscattering is possible are calculated. In this case, the source antenna is omnidirectional with $12dBi$ gain, and the PWSN node is equipped with a half-wave dipole, as discussed in 2. The results are shown in Fig. 3.4.

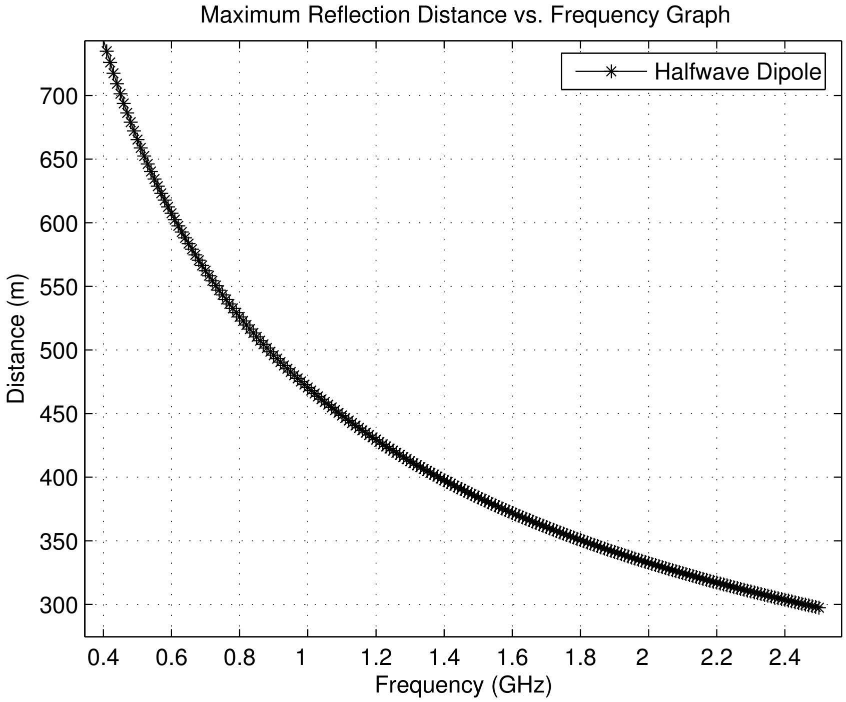

Figure 3.4: Maximum communication range by modulated backscattering for the half-wave dipole.

The maximum distance of communication at $1GHZ$ is around $470m$, which makes the modulated backscattering a practical option for PWSN. Consequently, it is clear that nodes fed by an external RF source can form an effective PWSN with sufficient coverage.

The results obtained above prove that passive communication is an advantageous method to be considered for PWSN. A detailed discussion on the possible approaches for communication in PWSN are presented next.

CHAPTER 4

COMMUNICATION IN PWSN

From the results of Section 3, it is evident that PWSN is feasible and achievable. The communication techniques to be used in PWSN, however, remain to be examined. In this section, we will first investigate, whether conventional communication schemes, which employ active transmission, can be adapted to PWSN. Then, modulated backscattering, as well as hybrid architectures are considered for PWSN.

4.1 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 PWSN nodes may employ conventional active transmitters. Depending on the power intercepted and stored by the nodes, the nodes may be operated continuously or not. Following are the considerations on continuous and discontinuous operation.

4.1.1 Continuous Operation

In this scheme, PWSN is analogous to the existing sensor networks, apart from being powered by RF signals, rather than batteries. However, the whole topology should be fed continuously, i.e., by an omnidirectional antenna. As observed in Fig. 3.3, only the nodes closer than $4m$ to the source may be fed continuously. Hence, such a system may not offer a sufficient coverage. To achieve a larger coverage, very high power levels are required and it may not be practical to supply the required levels of power in the sensor field. For civilian applications, the RF emission regulations limit the emitted power level, hence PWSN operation. On the other hand, supplying such high levels of power is a disadvantage for tactical purposes, when the detectability of the sensor network is concerned. The high RF power levels will make the network easily noticeable.

4.1.2 Discontinuous Operation

Another scheme of active transmission is discontinuous operation, in other words, “store-and-transmit”. In this scheme, PWSN nodes, which do not receive adequate power to operate continuously, store the RF power in a capacitor. This scheme may offer increased coverage, but may fail in time critical applications. The emergence of the ultracapacitors, on the other hand, makes this option feasible. Since the ultracapacitors enable the nodes to operate for considerable durations, even though no RF source exists, the discontinuous operation is of interest.

4.2 Modulated Backscattering as the Communication Technique for PWSN

In Section 3, it is observed that communication by modulated backscattering is conceivable for PWSN. However, using modulated backscattering results in a number of problems. Since the RF signal source is unique, the information transmitted from each node will be of the same frequency. Each node’s information should have a signature, and the information transmitted should not be suppressed by the signal from the RF source.

On the other hand, the advantages offered by modulated backscattering are very attractive. Since the total power consumption will decrease due to lower transmission power budget, the power requirement will drop for the nodes. This reduction of power requirement will result in longer sensor operation time on its capacitor, and lower RF power levels at the sensor field, which means a harder-to-detect sensor network.

Modulated backscattering offers another interesting opportunity to the PWSN designers. As observed in Fig. 3.4, the maximum communication range between a halfwave dipole and an isotropic source at $1GHZ$ is around $470m$. The power consumption of the node is merely due to the resistance switching. Clearly, communication with the PWSN nodes at mid and long distances is attainable by modulated backscattering, and the related power consumption at the PWSN node is considerably low, compared to active transmission. Utilising this opportunity, mid and long range communication links within the PWSN nodes may be employed together with short range hop by hop communication, at a constant transmission power cost per node (namely, the cost of load resistance switching). *However, this original approach requires a thorough investigation and development of a dedicated PWSN communication protocol stack.*

Similarly, all the nodes in PWSN can form a long-distance communication link with a distant user. Hence, any node in the PSWN can possibly act as a sink, providing the data flow from PWSN 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.

Feeding the nodes by a moving source is also an option to be considered. In this scenario, a moving source with a directive antenna feeds the nodes in its range and collects information from the event area. The use of a directive antenna increases the maximum source-to-node distance, which is observed in Fig. 3.3. Furthermore, the detectability of the network drops considerably, since there is no high power level existing continuously on the sensor field.

4.3 Hybrid Methods

There are numerous advantages of modulated backscattering as previously observed. The emergence of the ultracapacitors, however, enables nodes to operate without RF sources in the vicinity. A combination of both methods, i.e., hybrid architecture, which utilizes the advantages of both architectures, might be very useful for PWSN. In this scheme, sensor nodes continue to sense and compute even though no RF power signal is incident. Contrary to the modulated backscattering-only approach, the nodes may be capable of sending messages to the RF source even when it is not incident on them. By this way, they may inform the source about an urgent event and request RF power for continuous operation in the event area.

CHAPTER 5

PWSN COMMUNICATION PROTOCOL SUITE

The communication technique assumed for PWSN is a determining parameter for the protocol suite analysis. If active transmission using RF power is chosen as the communication approach, and continuous operation is expected, the operation of PWSN is similar to conventional WSNs, except its power source. Thus, existing WSN protocols might be applicable to PWSN employing active transmission with their nodes operating continuously. Consequently, here, we mainly focus on PWSN using active transmission with discontinuous operation, modulated backscattering and hybrid communication schemes. The applicability of existing protocols to PWSN and the distinct requirements of PWSN protocol stack are investigated. The anticipated challanges for networking and reliable communication in PWSN are discussed along with the open research areas.

5.1 Physical Layer

Due to its unique communication and power circuitry, the physical layer requirements of PWSN differ significantly from the conventional WSN requirements. Hence, the solutions for the communication and power circuitries of WSN are inapplicable to the PWSN domain. Clearly, the physical layer of PWSN should be treated as a completely new design problem. In this respect, the power and communication problems of PWSN should be discussed separately.

At the physical layer, the advancement of RF power scavenging and storing systems are crucial for the development of PWSN. The antennae design, signal waveform and bandwidth should be optimized for maximum power transmission efficiency. On the other hand, the utilization of the transmitted power at the node is a determining factor on the efficiency and the lifetime of PWSN. The RF-to-DC conversion of the intercepted power, in this respect, arises as another important issue to be considered. Power transmission at lower signal levels should be enabled and the efficiency of the converters should be improved. The increased storage capacity and efficiency of the capacitors would also improve the performance and lifetime of PWSN.

Theoretically, modulated backscattering is an effective communication method for PWSN. The transmitter circuitry is extremely simple, but the receiver to receive the backscattered signals should be highly sensitive. The power consumption, size and the complexity of this receiver should be reduced considerably in order to meet the requirements of PWSN. In this respect, a detailed inspection of the modulation techniques is also necessary, in order to to simplify the receiver and increase the system performance.

The nodes in the vicinity of a PSWN node reflect high power RF signals. The effect of these reflected signals on the node's power unit and receiver should also be investigated. In addition to that, the cumulative behavior of the reflected signals remains to be examined. The performance of the receivers in the presence of these reflected signals should also be investigated.

Some of the open research issues regarding the physical layer design in PWSN are outlined as follows:

- Increasing the efficiency of the RF-to-DC converters.
- Improving the performance of the capacitors.
- The optimization of antennae, signal waveform and bandwidth for both power transmission and modulated backscattering.
- Simple and cost-efficient receiver design for PWSN.
- Investigation of the cumulative behavior of reflected signals, also their effect on the PWSN node's transceiver and power unit.

5.2 Data Link Layer

The data link layer problems of PWSN deviate from the conventional WSN problems. First, the PWSN error control mechanism requires a thorough investigation. Altering the output power of the transmitter, hence the signal-to-noise ratio is one method of error control. Here, it should be noted that these *Power Control* schemes are inapplicable to PWSN employing modulated backscattering, since the PWSN node is incapable of varying the intensity of the incident signal. However, *Power Control* schemes should be considered for the PWSN nodes having active transmission capability (as in Setcion 4.1 and Section 4.3). The alternative error control mechanisms, i.e., *Automatic Repeat reQuest (ARQ)* and *Forward Error Correction (FEC)* should also be investigated for PWSN. To be more specific; the retransmission of data, which is the main method of *ARQ* based schemes, may not be practical at the presence of a mobile RF source. The power consumption due to *FEC* based schemes should be compared to the communication power cost in a real PWSN environment, and may turn out to be infeasible. Consequently, the PWSN error control mechanism design requirements will be clear after a detailed PWSN physical layer investigation.

Medium access control in PWSN is also a challenging issue. The existing MAC layer solutions for sensor networks may be grouped as reservation-based and contention-based protocols [2]. These two types of protocols can be analyzed separately for PWSN.

5.2.1 Reservation-Based Protocols

Reservation-based protocols generally employ time division multiple access (TDMA), and require a cluster-based architecture, in order to have the time slot assignment to be made by a local cluster-head. Using a reservation-based protocol for PWSN may bring several advantages. First of all, all nodes of PWSN share the same medium and the same signal to communicate. Thus, the frequency and modulation of the signal they reflect is the same. Hence, a TDMA approach may be very advantageous for PWSN. Additionally, communication with the RF source should be carried out by a limited number of nodes, in order to avoid contention at the source, and these nodes should collect information from the surrounding nodes. Hence, a cluster hierarchy is inherent in PWSN using modulated backscattering, if the RF source is to communicate with multiple nodes. The resulting hierarchy makes it convenient to implement a reservation-based protocol in PWSN.

On the other hand, a number of disadvantages are foreseen in using a reservation-based protocol. The delay by TDMA may cause problems, especially in time critical applications and if an RF beam from a mobile source is tracked by PWSN. Moreover, a contention or set-up phase is necessary for the cluster-heads to assign the time slots to the surrounding nodes. If an RF beam is tracked by PWSN, such a phase may lead to an intolerable delay (e.g., loss of the beam during the setup phase) and interrupt the operation of PWSN. Furthermore, synchronization is needed to achieve TDMA. For the PWSN nodes, which wake up and run out of power occasionally, time synchronization may be hard to attain.

5.2.2 Contention-Based Protocols

The major alternative of reservation-based protocols are contention-based protocols, in which the nodes listen to the channel and try to access accordingly. The lower delay of contention-based protocols makes them preferable for time critical applications. In addition, no cluster hierarchy is required for these protocols. If the RF source communicates with a single node (i.e., PWSN has a single sink), the utilization of contention-based protocols is appropriate, with the elimination of cluster hierarchy.

The higher collision probability with increasing node density is an inherent property of contention-based protocols. The collision problem of nodes, which modulate and reflect the same signal, is to be investigated. On top of that, the presence of a high power RF signal which is likely to interfere with the reflected signals makes the collision problem more complicated. In this regard, a detiled analysis on the physical layer characteristics of PWSN is needed to attack the collision problem in a typical PWSN environment.

Mid and long range communication within PWSN is theoretically attainable and offers an original approach to the WSN paradigm as introduced in Section 4.2. However, significant modifications in the MAC layer are needed to take advantage of mid and long range communications, and most probably, the development of a dedicated MAC method to utilise this property will be required.

The envisioned open research issues at the PWSN data link layer design are listed as:

- Specification of PWSN error control mechanism requirements after a thorough investigation of PWSN physical layer characteristics.
- Development of fast set-up methods for reservation-based protocols.
- Design of synchronization mechanisms for PWSN.
- Investigation of collision in the presence of reflected signals from the surrounding nodes and the RF source.
- Design of hybrid protocols, which utilize the stated advantages and suppress the disadvantages of reservation-based and contention-based protocols for PWSN.
- Design of a MAC protocol to take advantage of mid and long range communications in PWSN.

5.3 Network Layer

A number of routing protocols have been proposed to meet the specific network layer requirements of WSN [1], [2]. The proposed protocols are grouped as data-centric and flat-architecture, hierarchical, location-based and QoS-based protocols [2]. The applicability of these protocols to PWSN are investigated in the following and the special requirements of PWSN routing problem are discussed.

5.3.1 Data-centric and Flat-architecture Protocols

Data centric and flat-architecture protocols offer a simple solution to the routing problem in PWSN. The power level at the nodes in any part of the network is a varying parameter, resulting in a very dynamic environment. The simple solution offered by data centric and flat-architecture protocols, mostly assuming a static or slowly changing network environment, do not seem to match with the unique dynamic nature of PWSN.

5.3.2 Hierarchical Protocols

As mentioned in Section 5.2.1, the cluster hierarchy is inherent in PWSN at the MAC level, if the RF source is to communicate with multiple nodes. If cross-layer coordination is implemented and the hierarchy at the MAC level is used in the network layer, employing hierarchical protocols would be an appropriate choice. The power consumption and the delay introduced by the setup phase of the routing protocol are eliminated. Additionally, the possible failure of the cluster-head decreases the robustness of the conventional WSN. However, PWSN may replace the failed cluster-head by any node in the vicinity, due to the long range communication capability by modulated backscattering.

If the network is fed by a mobile or rotating RF source, on the other hand, the maintenance of the cluster hierarchy will be difficult. Due to the varying incident power levels on the nodes, nodes will have to change state between on and off frequently. The resulting dynamic network will require significant computing and communication overhead, in order to adapt its cluster hierarchy rapidly. Hence, employing hierarchical protocols does not seem practical for a PWSN which is fed by a mobile or rotating RF source.

5.3.3 Location-based Protocols

Location-based protocols require the location information of the nodes. The hardware to obtain the location information (e.g. GPS receiver), is both too expensive and too complicated to be feasibly installed on every node and significant power should be consumed for location finding. In a PWSN which is fed by a directive antenna, on the other hand, there exists the information of the node's alignment with respect to a reference point. In the event that the source is mobile, and broadcasts its location information with the alignment of its directive antenna, assuming the source has location finding capability, the PWSN nodes may get their relative angle to different reference points. Collaborative processing of these data from all the nodes may result in a feasible method of location finding for the PWSN nodes. It should also be kept in mind that the broadcast of location information and the antenna alignment are risky operations, if the detectability of PWSN is concerned. If the above mentioned method can be effectively implemented, the location based protocols might be suitably applicable to PWSN.

5.3.4 QoS-based Protocols

QoS-based protocols generally attempt to minimize the energy consumption of the network by using the remaining energy of the sensor nodes as a metric of optimization [2]. This approach has been modified in [10], regarding the power flow into the WSN, which fits into the PWSN network layer design problem.

For PWSN using modulated backscattering, however, the existence of the 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 this case. For active communication and hybrid architecture cases, on the other hand, existing protocols can be modified so that PWSN nodes demand for power, in case an event is detected. Such an operation requires a completely new routing protocol design.

Using QoS-based protocols, the existence and location of the RF beam can be observed within the network. By relevant modifications, tracking the RF beam in the PWSN network layer may be achieved by a QoS-based protocol. By this way, the data collected may be concatenated and processed in a route following the RF beam, and be sent immediately to the source whenever requested.

Regardless of the above mentioned protocols, an original approach to PWSN exists as introduced in Section 4.2. In this approach, mid and long range communication links within the network are employed together with short range hop by hop links. However, existing network protocols all assume hop by hop communication. To make use of the mid and long range communication capability, a completely new routing protocol for this purpose need to be designed.

The open research issues regarding the network layer design in PWSN are listed as follows:

- Cross-layer coordination of hierarchical routing protocols and reservation-based MAC protocols .
- Design of a feasible location finding algorithm for the mobile RF source case.
- Development and investigation of QoS-based protocols to enable demanding RF power.
- Modification of existing QoS-based protocols to implement tracking the RF beam.
- Development of a new routing protocol to employ the mid and long range communication capability.
- Investigation of effective interaction with other layers.

5.4 Transport Layer

The main objectives of the transport layer are to provide reliable data delivery and to control the congestion in the network. The proposed transport protocols for WSN are all based on active transmission, hence they are not completely applicable to PWSN employing modulated backscattering and hybrid methods. In a PWSN environment, the transmission of the nodes is highly correlated with the RF beam and the available power at the nodes. The characteristics of congestion in such a PWSN environment differs largely from that of a conventional congestion problem. After a complete investigation of the physical, data link and network layer characteristics of PWSN, congestion in PWSN needs to be clearly defined. Then, a dedicated mechanism to control the newly defined congestion should be developed.

Similarly, the reliable data delivery in PWSN 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 PWSN environment is also necessary. Hence, a method to provide the newly defined reliability should be designed for the PWSN.

The open research issues regarding the transport layer design of PWSN are outlined as follows:

- Definition of congestion in the PWSN domain and development of a dedicated mechanism to control the newly defined congestion.
- Definition of reliability in the PWSN domain and development of a dedicated method to provide the newly defined reliability.
- Development of a new and complete PWSN transport layer solution.
- Investigation of effective interaction with other layers.

CHAPTER 6

UWB PWSN MAC

As discussed in the previous chapters, the source of energy for PWSN, as alternative to the batteries of conventional WSNs, is an RF power source. Unlike conventional wireless sensor networks (WSN), PWSN has no lifetime limitation, it is not a disposable system, hence more functional, cost efficient and feasible. However, the practical realization of PWSN requires solutions for a number of open research issues. Among these issues, the medium access of PWSN nodes, which share the same medium and the same signal to communicate, arise as a major problem chapter:protocolsuite.

In general the randomly deployed low power WSN nodes require a dedicated solution for medium access, in order to meet WSN's unique specifications [2, 7]. However, the proposed solutions so far [7] assume actively transmitting WSN nodes. The medium access problem of PWSN differs from the conventional WSN medium access problem. First of all, PWSN nodes share the same medium and the same signal to communicate. On the other hand, the PWSN nodes should communicate in the presence of the high power RF signal from the source, and reflected signals from the surrounding nodes.

In order to address this problem of PWSN medium access, an original joint physical layer - medium access layer protocol is presented in this chapter.

6.1 The PWSN MAC Problem

In PWSN, the incident signal from the RF source is reflected by the PWSN nodes. The nodes modulate this reflected signal by changing the impedance of their antennae, thereby communicate their data passively. This scheme, i.e., modulated backscattering, is a simple and energy efficient method of communication. However, using modulated backscattering results in a number of problems.

Since the RF signal source is unique, all PWSN nodes reflect the same signal to communicate. The probability of collision is significant, if a contention-based method is employed. A TDMA approach may be a solution, however synchronization is imperative to achieve TDMA. For the PWSN nodes, which operate as long as power is delivered from the RF source and remain idle when there is no incident RF beam, time synchronization is likely to be hard to attain. On the other hand, for a TDMA scheme, a cluster hierarchy and a contention or set-up phase is necessary for the assignment of time slots to the PWSN nodes, which brings extra processing and delay.

Moreover, the presence of a high power RF signal, which is likely to interfere with the reflected signals, makes the PWSN MAC problem more complicated. In addition, the information transmitted should not be suppressed by the signal from the RF source. Extracting the low-amplitude reflected signal from the source RF signal necessitates advanced filtering techniques, which, in turn, require an excessive amount of processing power and energy.

6.2 UWB Communication in PWSN

Using an Ultra-Wideband (UWB) signal on the RF source, alternatively, proposes a number of interesting solutions to the above stated problem, given the unique PWSN characteristics. Before stating these solutions, it should be recalled that UWB systems employ noise like, wideband, short duration pulses to communicate [8, 22]. They usually have receivers of low complexity, low cost and resistant to severe multipath.

A key opportunity offered by the short duration UWB signals is that they provide a very high time domain resolution, enabling accurate distance estimation [6]. Accordingly, UWB systems are employed at a number of location estimation and ranging applications. These ranging techniques are usually based on the estimate of the distance between transmitter and receiver from the Time of Arrival (ToA). In

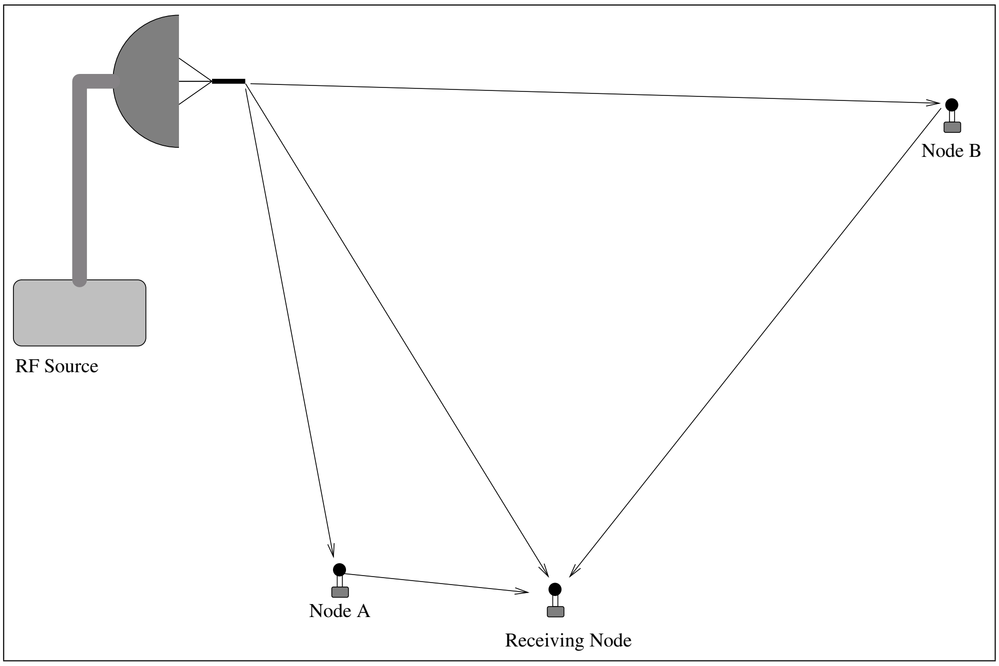

Figure 6.1: An UWB PWSN communication scenario, in which both node A and B communicates with the receiving node.

other words, for any given receiver, the ToA information contains information about the relative location of a transmitter.

6.3 The Joint Physical - MAC Solution Overview

In PWSN, the ranging capability of UWB systems is employed with a completely new approach. In our new approach, RF source emits a short duration UWB pulse periodically. The PWSN nodes utilize this pulse for both extracting power and communication.

For internode communication, each node reflects the UWB pulse to a destination node. Here, the random deployment of PWSN assures that the paths (from the source to any reflecting node + from the reflecting node to the receiving node) are most likely of different lengths. Since all the nodes reflect the same signal, i.e., the traveling of the signal is initiated by the RF source at a specific instant, the reflected signals from any node most likely arrive at a given receiving node at different phases, due to different lengths of paths they travel. In Fig. 6.1, the diverse paths that the reflected signals travel can be observed for a UWB PWSN communication scenario.

As seen in Fig. 6.1, the length of a path from the RF source to the receiving node via node A is much shorter than the length of a path from the RF source to the receiving node via node B. If we assume that a pulse in Fig. 6.2 is emitted from the RF source, the received pulses at the receiving node can be represented as in Fig. 6.3. In Fig. 6.3, the leftmost signal is the pulse from the source. Since it travels the shortest path, it is received first. The pulse coming through node A comes later and finally the pulse coming through node B arrives, traveling the longest path. The pulse from the source is also of highest amplitude, because it is not reflected, hence does not suffer from any attenuation at the reflecting node's antenna and again because it travels the shortest path.

Figure 6.2: An example UWB pulse emitted from the RF source.

By this method, for a given node, the pulses from the surrounding nodes arrive at different instances. What we here achieve is actually a basic TDMA scheme. The major differences of this scheme from traditional TDMA systems may be listed as follows:

- **Need for synchronization**: Synchronization, which is hard to attain for PWSN nodes, is needed to achieve TDMA, as discussed above. For the UWB PWSN MAC case, the source signal forms a reference timing signal for the nodes, and the reflected signals arrive after a characteristic delay, depending on the reflecting nodes' locations. As a result, pulses from different nodes arrive at diverse time slots. Therefore, no extra time synchronization is required for the proposed scheme, which is a major advantage over conventional TDMA systems.
- **Need for hierarchy**: Since no time slot assignment is necessary, a cluster hierarchy is not a requirement for the UWB PWSN MAC. The random topology of the PWSN provides the slot assignment task.
- **Need for a contention or setup phase**: As previously mentioned, in a traditional TDMA approach, a contention or set-up phase is necessary for

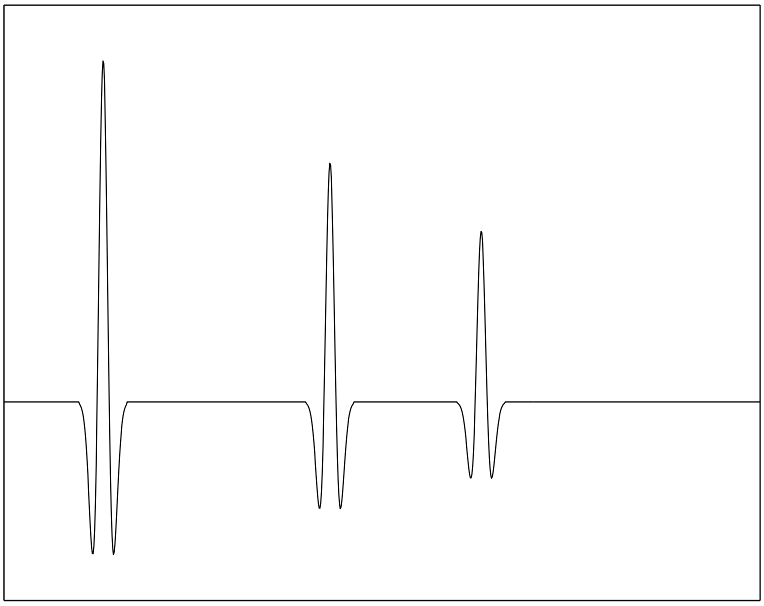

Figure 6.3: The received pulses at the receiving node.

> the cluster-heads to assign the time slots to the surrounding nodes in PWSN, which brings extra processing and delay. However, the time slot assignment is automatically achieved by the utilization of spatial diversity of the PWSN nodes. Hence, the setup phase needed at the proposed scheme should only handle minor problems, resulting in a much simpler and faster setup phase for PWSN.

Considering the stated advantages and its appropriateness for the unique requirements of the PWSN domain, we attempt to develop this MAC approach for PWSN. From this point on, we call our approach *UWB PWSN MAC*. Here it should be noted that *reversing the popular UWB ranging approach of extracting spatial information from the temporal diversity of the received signals, by the UWB PWSN MAC approach, we attempt to obtain a temporal distribution from the spatial distribution.*

Next, the details of a formal UWB PWSN MAC Protocol are presented.

6.4 The UWB PWSN MAC Protocol

Although time slot assignment period is not required in the proposed scheme, since the time slot assignment is automatically achieved by the utilization of spatial diversity of the PWSN nodes, there are a couple of issues to be handled by a medium access protocol. These issues can be listed as the the *pulse repetition period formation* and *collision avoidance*, and will be presented in the following subsections.

6.4.1 Pulse Repetition Period Formation

The repetition period of the source pulse is of utmost importance. Since the nodes reflect the source pulse to communicate, the bit rate of each transmission is determined by the rate of the source pulse repetition. Hence pulse repetition period determines the bitrate of the links, thus the throughput of the whole network and bandwidth utilization.

To achieve the maximum rate, a simple mechanism is offered within the UWB PWSN MAC, in a phase called the *PRP Decision Phase*. In this mechanism, the source signal initially operates with a predetermined long pulse repetition period (PRP). This initial period of the *PRP Decision Phase* is called the *Minimum PRP Discovery Period*. In *Minimum PRP Discovery Period*, first, the long PRP continues to operate, and every PWSN node reflects the source pulse, by keeping the their reflectors on during this phase. Simultaneously, each PWSN node discovers and records at what instance it receives a reflected pulse, which is of detectable amplitude. The instance is determined with respect to the reference source pulse. After a number of cycles, each node discovers when the latest detectable pulse arrives. The duration between the arrival of the reference pulse and the latest received signal is the minimum PRP for the given node.

After the *Minimum PRP Discovery Period*, the *Minimum PRP Broadcast Period* begins. At the *Minimum PRP Broadcast Period*, every PWSN node accesses the channel one by one. Here, we assume that each node has a global ID, and the nodes follow the order of their global ID's to guarantee the channel access on a queue. When a node accesses the channel, (i.e., modulates the reflected signal while the others keep their reflectors off), it broadcasts its ID and its minimum PRP. During the *Minimum PRP Broadcast Period*, the source collects the data from every node, and at the end of the *Minimum PRP Broadcast Period*, picks the maximum of the listed minimum PRPs and sets it as its current PRP. The *PRP Discovery Phase* terminates by the broadcast of the resulting PRP.

This method both guarantees that no node in the network suffers inter symbol interference and the maximum achievable rate is obtained.

6.4.2 Collision Avoidance

Even though the probability of collision of pulses from two different nodes at another is intuitively low, the collision is an issue to be handled by the MAC protocol at the *Collision Avoidance Phase*.

In the *Minimum PRP Broadcast Period*, each node broadcasts its ID and its minimum PRP, while the other nodes are silent. Since each node broadcasts its global ID with its PRP, the listening nodes detect at which instant a pulse arrives from a unique neighbor node. Hence, the *Minimum PRP Broadcast Period* of the *PRP Decision Phase* is simultaneously the *Collision Discovery Period* of the *Collision Avoidance Phase*.

At the end of the *Collision Discovery Period*, every node has a list of the time slots, at which they receive pulses from known neighbor nodes. Finally, a basic check of overlapping pulse arrival times is made on each node. Following the order of their global ID's, every node broadcasts whether it suffers from collision, and if it does, the ID's of the colliding reflector nodes. This period is called the *Collision Broadcast Period*. The source receives this information, picks one of the colliding nodes randomly, and orders the transmitter of the selected node to be turned down. These decisions are broadcasted through the whole PWSN by the source, finalizing the *Collision Avoidance Phase*.

In this respect, we assume that the collision of pulses from two nodes, which are closely deployed (i.e. distance less than the tolerable resolution) is most likely. Since the data from these closely located nodes are highly correlated, the access of both nodes is not crucial to improve the performance of the system. Hence, the source picks one of the colliding nodes randomly and and orders the transmitter of the selected node to be turned down. However, the node, which turns its transmitter down, remains on, and listens to the ongoing communications. If necessary, the turned down node may become active and join the PWSN as a backup. A small modification to the UWB PWSN MAC providing this property can introduce a significant resilience to the PWSN.

Consequently, a simple MAC protocol is designed to handle collision and pulse repetition period determination. The proposed simple protocol is summarized in Fig. 6.4.

6.5 The Feasibility and Performance Evaluation of the UWB

PWSN MAC

Here, the analysis of the feasibility and the efficiency of the proposed UWB PWSN MAC is performed. In the first part, the probability of collision of the pulses is inspected, in order to see whether effective slot assignment is practical with UWB PWSN MAC for a typical PWSN deployment. Next, the maximum achievable link rate of UWB PWSN MAC is investigated to evaluate the performance of the proposed protocol.

The spatial resolution vs. temporal resolution characteristics is of primary concern in the analysis of the proposed system. In this respect,the probability of collision of pulses from two different nodes at another is as follows.

$$\begin{aligned} P_{collision} &= P\left(\frac{|(d_{SA}+d_{AR})-(d_{SB}+d_{BR})|}{c} \leq \tau\right) \\ P_{collision} &= P\left(|(d_{SA}+d_{AR})-(d_{SB}+d_{BR})| \leq \tau c\right) \qquad (6.1) \end{aligned}$$

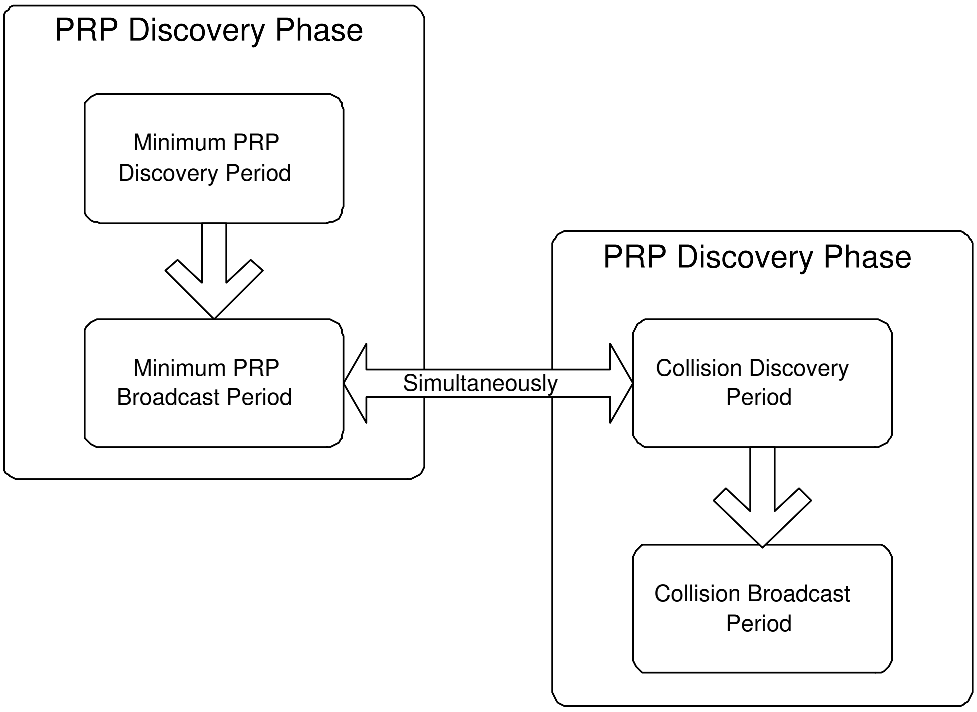

Figure 6.4: A summary of the proposed protocol.

where d_{SA} is the distance from the source to node A, d_{AR} is the distance from node A to the receiving node, d_{SB} is the distance from the source to node B, d_{BR} is the distance from node B to the receiving node. These nodes can be seen in Fig. 6.1. c is the speed of light and τ is the pulse duration.

A practical pulse width τ assumption of $0.2ns$ [15] results in a τc multiplication of $6cm$. In other words, as long as the length of the paths that two different signals are separated by more than $6cm$, it is guaranteed that the reflected signals do not collide at the receiver.

After the probability analysis, we perform a simulation to see the practical collision problem at UWB PWSN MAC. The simulation presents the results of a typical *Collision Discovery Period.* In the simulation, a random distribution of 50 PWSN nodes are deployed in a $200m$ by $300m$ field, as shown in Fig. 6.5. The RF source is located on the lower boundary of the topology and τ is assumed to be $0.2ns$.

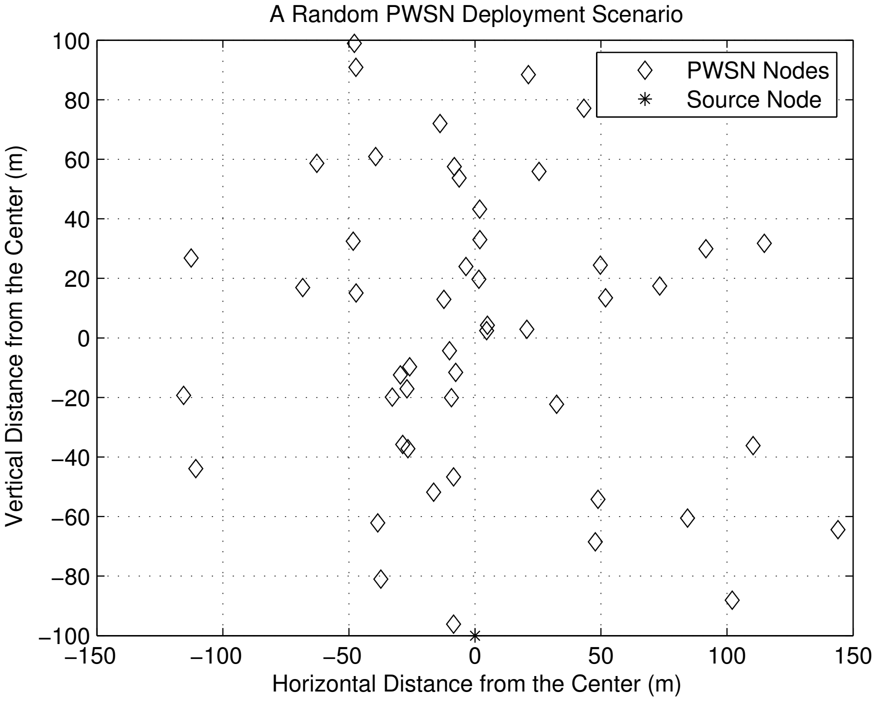

Figure 6.5: An example PWSN topology.

First, for a given node, the path lengths from the source through every other node in the network are calculated. Then, the traveling times of pulses on these paths are evaluated. The resulting list provides, for a given node, the traveling times of pulses from all the other members of the PWSN. In this list, any two pulses with traveling times, which are closer to each other than τ, are going to collide. What we here obtain is actually a *Collision Discovery Period* cycle for a single node. When we repeat the experiment for the remaining nodes of the PWSN, we get a complete *Collision Discovery Period*. The number of colliding links for each node are summed up in the end, providing the total collision metric for a PWSN deployment. The simulation is repeated 1000 times for newly generated random topologies, and the resulting number of collisions are presented in Fig. 6.6.

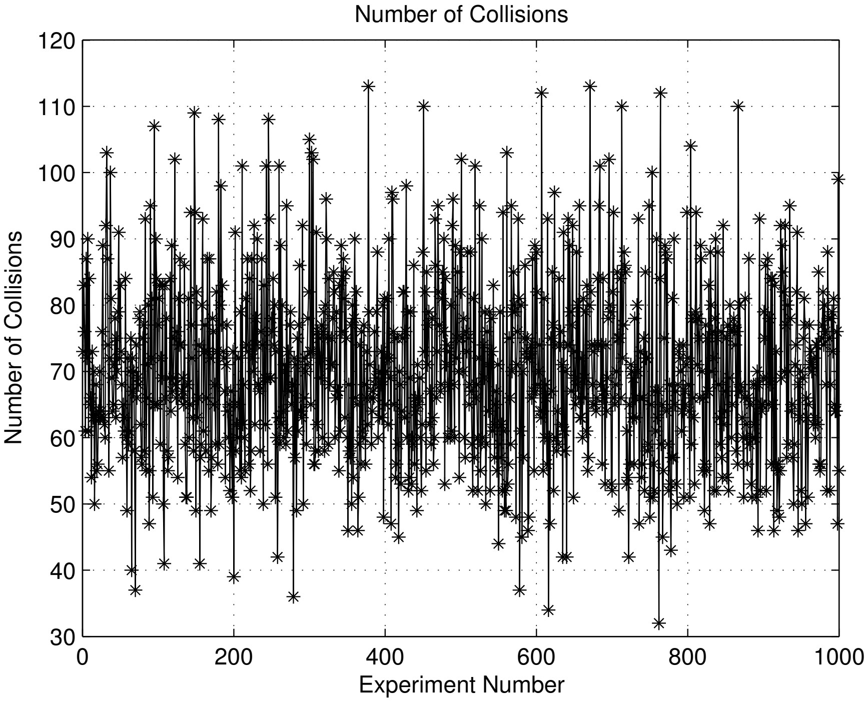

Figure 6.6: Collision simulation results.

The average number of colliding nodes is 69.9 for a single simulation. When the total number of links in a 50 node topology is concerned, i.e., 2450, the average number of colliding links is low. The average percent of colliding nodes is 2.85, which proves the feasibility of the UWB PWSN MAC. Here, it should be recalled that the collision of these nodes is efficiently handled at the *Collision Avoidance Phase*.

Next, the maximum achievable link rate of UWB PWSN MAC is investigated to evaluate the performance of UWB PWSN MAC. Given spatial distribution and source signal properties, the maximum achievable link rate is a crucial metric. To analyze the rate, the following simulation is performed.

In the simulation, again a random distribution of 50 PWSN nodes are deployed in a $200m$ by $300m$ field, as shown in Fig. 6.5. The RF source is assumed to be on the lower boundary of the topology, and is assumed to be transmitting $0.5W$, $0.2ns$ pulses from an $8.5dBi$ omnidirectional antenna. For the given topology, the *Minimum PRP Discovery Period* is simulated for every PWSN node. Here, for a given node, every path length from the source through every other node in the network is calculated, as in the *Collision Discovery Period* simulation. Then the pulse arrival times from every other node in the network are evaluated. The maximum pulse arrival time for the given node is the Minimum PRP of that node. When this process is repeated for the remaining nodes of the PWSN, we obtain a complete *Minimum PRP Discovery Period.* Simply by taking the maximum of the Minimum PRP's of PWSN nodes, we get the PRP of the given PWSN deployment. This simulation is repeated 1000 times and the maximum PRP lengths are observed in Fig. 6.7 for each simulation.

In Fig. 6.7, the maximum PRP is 2.24μs, thus the minimum observed pulse repetition frequency is $446KHz$, which leads to a rate of $446Kbps$, when no coding is involved. The mean of the PRPs of the simulation is 1.58μs, resulting in an uncoded rate of $633Kbps$. These rates are very promising, when the commercially available, actively transmitting WSN nodes' rates on the order of $10's$ of Kbps.

The above simulation provides only a sense of rate with respect to propagation times of the reflected signals. However, a significant attenuation is anticipated at communication by modulated backscattering. Next, we attempt to take the attenuation into account, and make a more realistic analysis.

Now, we assume that the PWSN nodes are equipped with $8.5dBi$ omnidirectional antennas and $-100dBm$ receivers. The first simulation is repeated, however now the reflected signals which are attenuated below the detectable level are discarded. The results of this simulation is presented along with the results of the first simulation in

Fig. 6.8, so that the effect of attenuation can easily be observed.

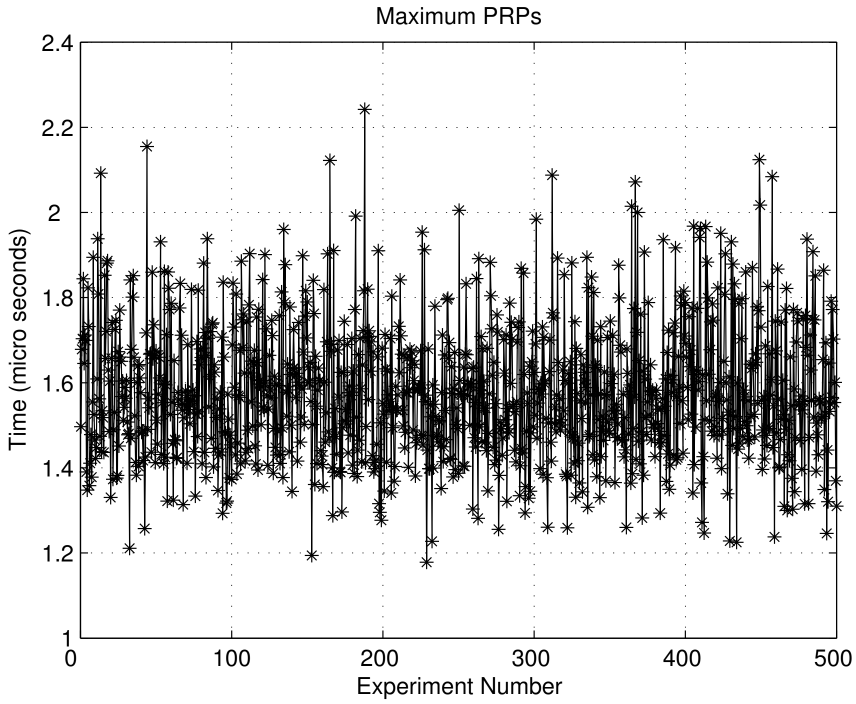

Figure 6.7: Maximum PRP lengths of the link rate simulation.

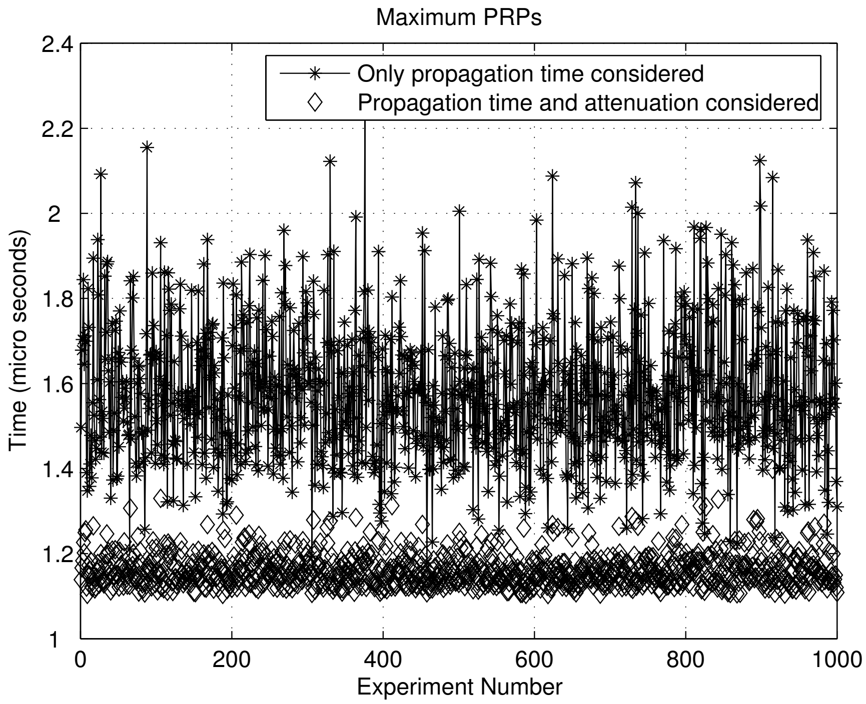

Figure 6.8: Maximum PRP lengths of the link rate simulation with attenuation taken into account.

The maximum PRP with attenuation taken into consideration in Fig. 6.8, is 1.4μs, thus the rate of $715Kbps$, when no coding is involved. The mean of the PRPs of the simulation is 1.16μs, resulting in an uncoded rate of $861Kbps$. The improvement over the first simulation is clear and expected, since discarding unuseful low amplitude signals increase the maximum pulse repetition rate.

Here, it should be recalled that communication at a few 100s of meters and at $10's$ of Kbps by the commercially available, actively transmitting WSN nodes has the energy cost of $10's$ of mWs. When compared, the proposed scheme offers passive communication by the nodes and a very high link rate.

Another inherent property of UWB PWSN MAC is the simplicity it offers for the PWSN node receiver. As seen in Fig. 6.1, the pulses from different reflecting nodes arrive at different instances. The detection of these short-duration pulses can easily be achieved by a simple threshold detector. This simplicity of receiver is a major advantage for the design of low complexity and low cost PWSN nodes.

A second reason for the simplicity of the receiver is that time synchronization is basically obtained by the reference pulses from the RF source. When the complexity of obtaining time synchronization for the distributed WSN nodes is considered [16], it is clear that being able to easily achieve the synchronization from the high amplitude periodic reference pulse is a major advantage.

6.6 Discussions

In this chapter, we introduced the UWB PWSN MAC, which is an original solution for the PWSN MAC problem.

The unique requirements of the PWSN MAC problem are met by reversing the popular UWB ranging approach of extracting spatial information from the temporal diversity of the received signals. UWB PWSN MAC obtains a temporal distribution from the spatial distribution, fitting in the random node distribution and single reflected UWB pulse assumptions of PWSN domain.

A simple UWB PWSN MAC protocol, consisting of PRP determination and collision avoidance phases is introduced. The feasibility analysis of UWB PWSN MAC is presented, together with a performance evaluation of the proposed protocol. The simplicity of the required receiver, the elimination of the need for synchronization together with the high rate performance of the protocol present UWB PWSN MAC as a competitive solution for the PWSN MAC problem.

CHAPTER 7

CONCLUSIONS

In this thesis, PWSN is introduced, which is theoretically free of energy constraints and has an infinite lifetime. The feasibility of the proposed system is studied, and it is discovered that PWSN is achievable. The PWSN nodes are powered by RF signals from an external source and modulated backscattering is employed in PWSN as a new communication technique. The unique requirements and characteristics of PWSN are stated and the communication protocol suite for PWSN is discussed along with the open research issues. Consequently, it is observed that PWSN is theoretically attainable and capable of introducing a novel approach to the design of wireless sensor networks. However, a number of research challenges remain to be investigated in the development of PWSN. Apart from the open research issues presented in this thesis, the characteristics of the PWSN physical layer and the practical aspects of PWSN design need to be thoroughly investigated.

Additionally, a novel solution for the PWSN MAC problem, which proposes obtaining a temporal distribution from the spatial distribution is presented. A protocol is described, and the proposed scheme's performance is analysed. The proposed method offers a simple, robust and fast solution to the PWSN MAC problem.

Finally, the open research issues, which are listed in Chapter 5 are reminded as challenging issues of the PWSN design. Although being a good match for the PWSN requirements, it is believed that the original idea of obtaining a temporal distribution from the spatial distribution can be extended to other distributed UWB wireless networks, and significant research opportunities are envisioned in this prospect.

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