iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 4 **Issue:** IX **Month of publication:** September 2016

DOI:

Volume 4 Issue IX, September 2016
ISSN: 2321-9653

International Journal for Research in Applied Science & Engineering Technology (IJRASET)

TPC for Industrial Wireless Instrumentation

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Abstract—The adoption of wireless technology for industrial wireless instrumentation requires high-quality communication performance. The use of transmission power control (TPC) can help address industrial issues concerning energy consumption, interference, and fading. This paper presents a TPC algorithm designed for industrial applications based on theoretical and empirical studies.
It is shown that the proposed algorithm adapts to variations in link quality, and is hardware-independent and practical.
Index Terms—signal-to-interference-and-noise ratio (SINR), signal-to-noise, ratio (SNR), transmission power control (TPC), Wireless HART, wireless sensor network (WSN)

I. INTRODUCTION

The Industrial wireless standards of Wireless HART (a trademark from Hart Communication Foundation), ISA100.11a, and Wireless networks for Industrial Automation- Process Automation (WIA-PA) underpin the use of wireless technology in the process industries for monitoring and noncritical control applications in oil and gas installations, refineries, and chemical plants. Considerations in industrial wireless networks include RF interference and the constraints of low-power industrial sensor nodes . Process automation applications require frequent periodic communication, which increases power usage.
Resources in a wireless network are limited and are subjected to regulations which mandate the need for efficient spectrum management. Efficient utilization of radio resources is up to the radio resource management (RRM) strategy and one such radio resource is transmission power level. Transmission power control (TPC) involves the adjustment of transmission power at the transmitting node to the minimum level which can ensure successful communication and maintain a given quality of service (QoS) .
One approach to TPC is to adjust the transmission power levels optimally during network design, taking account of the topology of the network . In addition, TPC algorithms can adjust transmission power dynamically to reduce energy consumption of a mobile terminal and prolong its battery life, to minimize co-channel interference in a shared medium, to achieve higher average spectral efficiency, and to address the fading issue during adverse channel conditions while constraining the bit error rate.
TPC is used in wideband code division multiple access (W-CDMA), a channel access technique used in the third generation of cellular technology [10]. The use of TPC is also compulsory for Bluetooth class 1 devices but optional for others . However, although TPC is widely used in these communication technologies, its use in short-range, low-power industrial wireless networks is new and has unique challenges. Support for TPC is included in the industrial wireless standards, but details of its implementation are not specified. It is, therefore, an avenue of research. Motivations for TPC in industrial application such as process automation include:

A. Energy savings by reducing transmission power to the minimum required;
B. Prolonging battery life for fast sampling applications;
C. Adaptation to continuing improvements in devices, particularly in terms of receiver sensitivity
D. Spectrum efficiency, topology control, and interference suppression to ensure co-existence .

This article proposes an adaptive multi-channel transmission power control (AMC-TPC) algorithm for industrial wireless networks such as WirelessHART, ISA100.11a, or WIA-PA. The main contributions of the paper are identification of the opportunity for AMC-TPC within these industrial wireless standards, systematic analysis of the requirements, and provision of an algorithm for AMC-TPC to work with devices that are compliant
with those standards. The algorithm built on empirical studies is shown to be adaptive and it supports multi-channel operation.

II. LITERATURE SURVEY

TPC has been proposed for wireless networks which include cellular, fixed point-to-point microwave links, Mobile Ad-hoc NETworks (MANETs), vehicular ad-hoc networks (VANETs),

wireless local area networks (WLANs), and wireless personal area networks (WPANs). TPC in cellular networks has been extensively studied, and many review papers have been published on the subject including [14]. The authors of [14] and [15]

consider that TPC will remain a key configurable component in future mobile network to ensure QoS. A common viewpoint is that collectively adapting power, modulation, and channel assignment can enhance throughput and energy use in network operations. However, the TPC strategies and methods for traditional networks cannot simply be replicated for industrial wireless sensor networks (WSNs). Reasons include use of the industrial, scientific, and medical (ISM) radio band; requirements of the industrial wireless standards; network classification and topology; off-the-shelf available transceiver hardware; inherent limitations of wireless sensor nodes; and predefined and fixed parameters such as modulation. The following sub-sections review some of the relevant literature, which can be classified into three categories:

Performance limitations of the IEEE 802.15.4 standard;
Link quality assessment; and
TPC algorithms for WSNs. Table I gives an

A. Performance Limitations of IEEE 802.15.4

Link budget is important for performance because it takes account of all the gains and losses from the transmitter to receiver through the propagation medium. If the received power is near the threshold of the receiver sensitivity, the packet error rate (PER) will rise. The work in [12] highlights the theoretical and practical sensitivity limits of the IEEE 802.15.4 compliant receivers. The investigation by [16] has summarized the impact of signal-to-noise ratio (SNR) on packet loss rate under additive white Gaussian noise and Rayleigh fading models, and further coexistence is studied through simulations in [17]. Empirical evaluation of the IEEE 802.15.4 network is carried out in [18] and has indicated the operational limitations.

Reference [19] highlights the impact of coexisting office Wi-Fi (IEEE 802.11b) networks on the PER of IEEE 802.15.4 networks and gives insights to the effect of interference on the link budget. The above work emphasizes factors affecting the theoretical and practical limits of the underlying physical layer used in industrial wireless standards. Furthermore, [20] studied the medium access control (MAC) protocol specified by the IEEE802.15.4 standard when power management is enabled. The results show that the nodes experienced low communication reliability. This unreliability issue was identified to be linked to the carrier sense multiple access with collision avoidance (CSMA/CA)-based algorithm. Even though this is a common issue for all CSMA/CA based MAC protocols, it is more prominent in the case of IEEE802.15.4 standard when operated with default parameters suggested in the standard. Although [20] showed that in some cases with appropriate parameter settings the reliability can be improved, in certain scenarios the parameters used were not compliant with the standard.

B. Link Quality Assessment

Link quality refers to the communication performance of a radio channel, which changes significantly with time and environment [21]. Received signal strength indicator (RSSI) and link

quality indicator (LQI) can be used as link quality metrics [21]–[23]. In [24], the authors conducted experiments to evaluate wireless link quality based on RSSI and LQI by varying distance and transmission power levels. The experiments presented in [22] further investigate the effect of interference on IEEE 802.15.4 receivers by varying transmission power, distance, orientation, packet size, and relative distance from interfering nodes.

The overall findings from the cited work are that in a rapidly changing environment and with limited resources, RSSI is a better indicator of link quality. RSSI is also better defined in the IEEE 802.15.4 standard compared to LQI [25]. The review in [26] highlights that evaluation of LQI is vendor-specific, whereas most transceivers include a RSSI register. The same reviewpaper discusses issues such as nonisotropy and the variability of link assessment in the transitional region. It compares hardwarebased link quality measures (RSSI, LQI) and software estimators.

Software estimators have higher energy consumption overheads for computation and communication, giving a further reason to use the hardware-based RSSI measurement in a TPC algorithm. An investigation aimed to study the speed-dependent PER of wireless sensor radios on rotating mechanical structures is presented in [27]. As a result, a predictive PER model for a fast rotating sensor radio channel based on channel impulse response measurements was presented. It takes into consideration power attenuation, bit error rate, received signal strength, and the radio receiver sensitivity.

C. TPC Algorithms

TPC algorithms rely on the availability of a range of transmission levels at the transmitter. The selection criteria for useful power levels within indoor environments are highlighted in [28] for Wi-Fi (IEEE) networks. In [29], an adaptive TPC algorithm is proposed where each communicating node builds a model for each of its neighbors, describing the relationship between transmission power and the link quality metric. A linear approximation is assumed between transmission power and RSSI. The authors in [30] have proposed algorithms for TPC based on an analytical model of RSSI. The signal-to-interferenceand- noise ratio (SINR) approximation in [30] assumes that interference is negligible, however. An investigation of the performance of TPC algorithms in terms of PER, power gain, and energy efficiency in additive white Gaussian noise and Rayleigh channels is presented in [31]. The TPC approach in [22] is based on tracking RSSI where the effect of radio channel uncertainty and interference were considered as disturbance.

Quantifiable improvements were shown in terms of reduced outage probability and power consumption. The algorithm proposed in [32] utilizes RSSI and LQI at the receiver to adjust the

transmission power. It was demonstrated that the proposed methodology yielded good link quality while saving power. In addition, an SINR-based TPC for wireless ad hoc networks is presented in [33]. However, it is studied through simulations and the control messages are transmitted using announcement traffic indication message (ATIM) within IEEE 802.11 distributed coordination function (DCF). Other theoretical or simulated studies include the following.

1) The Hybrid [34] is an example of TPC for MAC protocols in WSNs. Its algorithm iterates over available transmission power levels in order to achieve and maintain the target link quality.
2) The same authors [34] have also presented another TPC approach referred to as attenuation with exponentially weighted moving average (AEWMA) which utilizes the reception power, noise power, and transmission power in order to determine the ideal transmission power.
3) The local mean algorithm (LMA) [35] is proposed for WSNs where the transmitter counts the number of reachable neighbors at a particular power level, where value is adjusted if the received acknowledgments are less than what was expected.
4) A modification to LMA is the local mean of neighbors (LMN) algorithm where the receiver adds the number of its neighbor's neighbors to the acknowledgment packet [35], [36] to make the connectivity of its neighbors visible. Using this enhanced information, the transmitter makes power adjustments. This strategy does not require storing of a neighbors' table. It requires fewer resources and is based on number of reachable neighbors.
5) Kawadia and Kumar [37] have investigated whether TPC is to be implemented in the MAC or routing layer. They take into consideration the energy-efficient routes which incorporate links in a multi-hop network.
6) In the real-time power-aware routing (RPAR) protocol presented in [38], the dynamic power adjustment and routing decisions are made in order to minimize the packet loss rate. In addition, in the case of [39], topology control is studied in relation to power control. A distinction is made between power control approaches based on transmitting power levels available at the nodes, referred to as homogenous- (i.e., all nodes utilize same transmitting power level) and nonhomogeneous (i.e., different individual transmitting power level)-based topology controls.

TPC algorithms for industrial wireless systems are not well developed. Industrial wireless protocols have strict requirements, for instance, time slotted frequency hopping between channels [40]. For an industrial strength TPC, moreover, the algorithm has to be robust to interference. However, the performance of TPC algorithms is often reported for static channel deployments. In addition, the static channels are often in a different frequency band than a co-habiting Wi-Fi network, in order to avoid degradation due to interference. In an industrial environment, the changing link quality from one channel to the other and the effect of Wi-Fi on some channels compared to others has to be considered. Therefore, a TPC algorithm is required which can adapt to changing radio environment, is

quick to respond, works on a pair-wise basis to ensure topology independency and autonomous operations, and is practical.

Volume 4 Issue IX, September 2016
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International Journal for Research in Applied Science & Engineering Technology (IJRASET)

III. SYSTEM MODEL

A. Terminology

The following definitions are needed.

1) RSSI: Received signal strength indicator provides an estimate of the received signal power in the transmission channel [25]. It is the RF power input to the receiver [41], [44] given by where is signal power, is the total interference power, is the noise power, and is the interference from interferer number , and is the total number of interferers.
2) LQI: Link quality indicator is a metric of link quality; it may be implemented using receiver energy detection, SNR estimation, or a combination of these methods [29], [42]. The IEEE 802.15.4 standard does not specify how the LQI is to be measured. Some commercially available chips map LQI to SNR [43].
3) PRR: Packet reception rate is the time average of the ratio of number of received packets to those transmitted. It is a metric of link quality [24].
4) SNR: It is the ratio of strength of desired signal to noise. It is expressed as follows [44]:
5) SINR: It is the ratio of desired signal to interference plus noise. It is given by [44]

B. Requirements Analysis

The topology of an industrial wireless network is typically a simple star topology, but may also be a multi-hop mesh network. WirelessHART supports frequency hopping on per packet basis (fast hopping), while ISA100.11a supports both slow and fast hopping [2]. Generally, the TPC algorithm will need to operate over all the available channels, a maximum of 16 in the 2.4-GHz band. Each node will have its neighbor's information such as its unique identification number, allocated time slot, and channel number stored in communication tables. For each neighbor and for all available communication channels, a set of minimum

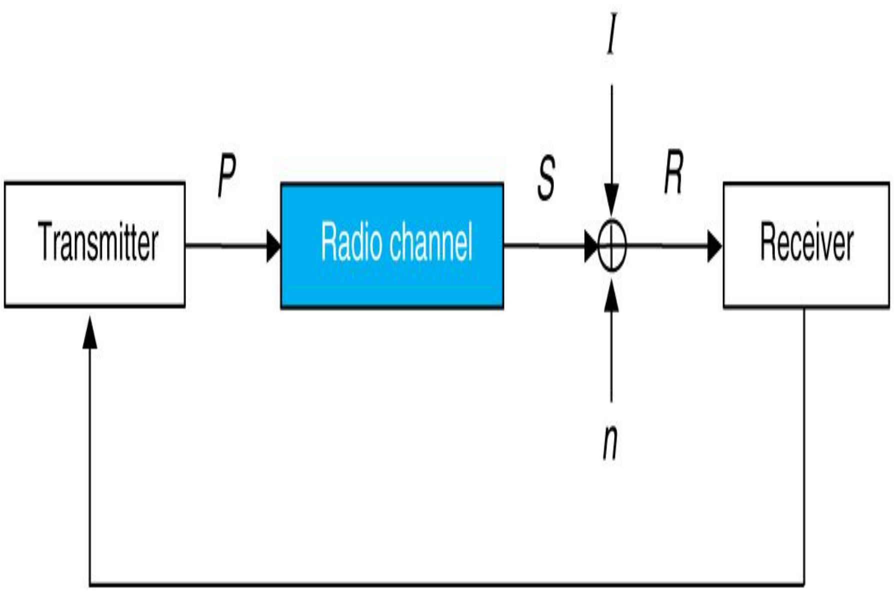

Fig. 1. TPC loop,

transmission power levels has to be estimated to ensure an adequate SINR.

The requirement for TPC is to estimate minimum transmission power level while ensuring:

1) Minimum overhead linked to TPC;
2) Adaptation to all channels and changing conditions;
3) Prevention of outages;
4) Independence of hardware platform;
5) Adaptability to asymmetric links, varying transmission power levels and sensitivity thresholds of the receiver.

C. Problem Formulation

Fig. 1 depicts a generic control loop for TPC. To the left of the figure is a transmitter operating at a transmission power level of , the RSSI value received by the receiver on the right is represented by . The block labeled Radio Channel represents the signal attenuation as it propagates.

The attenuation between transmission power and signal power depends on path loss and other properties of the channel such as shadowing. The signal is then subjected to interference and noise, and the final value is , reported as RSSI by the receiver. Interference between co-existing wireless networks has to be taken into account [19], [45]. Based on the work from [19], it was found that an IEEE 802.15.4 network experiences performance degradation if operated within 7 MHz of Wi-Fi (802.11b) channel and within a vicinity of 8 m, so the PRR and RSSI values will vary from channel to channel. These explanations show that higher values of RSSI in some channels may be attributed to interference, whereas channels without interference may have a lower value. The corresponding SINR will vary. Therefore, SINR estimation is important to ensure a specific threshold throughout the channels [16], [30].

1) SINR and SNR Estimation: In many cases, the main source of interference is a co-existing Wi-Fi network. The IEEE 802.15.4 channels whose frequencies overlap with the Wi-Fi network are referred to as in-band channels and those which do not overlap are called out-of-band channels. The use of Wi-Fi is often limited to three channels as adjacent Wi-Fi channels in them 2.4-GHz band overlap. This simplifies the process of identifying in-band and out-of-band channels. The amount of interference caused to in-band channels by a Wi-Fi network will depend on network traffic. However, beacons are broadcast at regular intervals by a Wi-Fi network and will result in a constant source of interference. Empirical data can be used to estimate the SINR and SNR. The equation for RSSI (1) can be used to obtain the approximation presented in (4), given that there is no interference. Here IB represents in-band and Si represents Signal.

A bar above, e.g., means an out-of-band channel which is not affected by interference. Further, as the IEEE 802.15.4 compliant devices provide a mechanism to perform clear channel assessment (CCA), they can be used to detect the energy present in a channel [43]. Without signal transmissions (i.e.,), in-band assessment results in (5), and out-of-band is represented by (6). Here, the channel energy indicator (CEI) is used instead of RSSI, because RSSI is associated with the signal. In the absence of a signal, channel energy can still be quantified. Therefore, CCA modes along with RSSI can be used to obtain the approximations given below SINR and SNR can be determined from RSSI and CEI.

These estimates are derived from empirical data, and can be approximated using a PRR test conducted over multiple channels. Periodic sampling of the radio channel in the absence of signal will quantify the noise power. Hardware linked noise power varies with temperature. However, it is quite stable over time periods of seconds or minutes [18]. These estimates along with the RSSI tracking will assist in the formulation of a TPC algorithm.

IV. DESIGN OF THE TPC ALGORITHM

The distributed nature of industrial wireless instruments and mesh networking requires a decentralized approach that is vendor independent. Requirements for the TPC algorithm are as follows: 1) it should execute pair-wise between two nodes at a time; and 2) it should track the link quality using RSSI rather than the vendor-specific LQI.

A. Overview of the TPC Algorithm

The algorithm provides feedback control to maintain SINR above a reference value by adjusting the transmission power level. Its main features are:

1) Estimation by the receiving node of the SINR of the communications link making
2) Computation of the transmission power level required for achieving the reference SINR value;
3) Generation by the receiving node of a TPC command;
4) Feedback of a TPC command from the receiver to the transmitter. The aim of the feedback is to reduce the transmission power to the lowest value which gives adequate SINR.

Detailed steps in the algorithm include:

1) Modeling the relationship between RSSI and transmission power at the receiver;

2) Building a TPC table in the transmitting node;
3) Making a TPC decision in order to determine whether a TPC command has to be forwarded to the transmitter;
4) Adjustment of the transmission power level in the transmitter by means of a power update controller.

B. *Building the TPC Table*

The TPC table models the linear relationship between transmission power level and RSSI for each link and each channel.

This model will be used to find the lowest value of transmission power required that will achieve the desired RSSI and, consequently, achieve the reference SINR. The algorithm establishes the TPC table during network setup making use of beacon packets which are transmitted periodically to announce the presence of the network. The table provides a relationship between transmission power and RSSI for all available communication links and channels. When a node has to transmit a packet, it consults the TPC table to identify the minimum transmission power required for communication with a specific node.

As each node may offer different levels of transmission power, let that be denoted by a vector

where element represents a discrete transmission power available at node denoted by index . is the number of available power levels.

A PRR test is used to find the linear relationship between the transmission power and RSSI. EachPRR test requires a few (e.g., 100) packets to be transmitted at a particular power level. For each received packet, a corresponding RSSI is recorded. The test is conducted using available transmission power levels starting from the maximum power level and proceeding toward lower levels. The test ends when the PRR value shows that the transmission power is too low for successful transmission.

RSSI and PRR are represented by and computed at the receiving node , respectively. Here is the average RSSI value recorded at the receiver corresponding to packet transmitted at power level Up to 16 channels may be available for communication between each transmitting and receiving node.

Therefore, a matrix is formulated as follows: Here, represents the channel number as defined by IEEE 802.15.4, and and are parameters describing the linear relationship between and . A matrix is built and stored for all available pairs of nodes and used to determine the transmission power required to yield a specific RSSI value at the receiving node. This RSSI value depends on a user-specified reference SINR. The computed transmission power values are conveyed to the transmitter where they are stored.

C. *Implementation of the TPC Algorithm*

The majority of the processing for the TPC algorithm takes place at receiver, while the actuation takes place at the transmitter. The working of the proposed TPC can be divided into two phases:

1) Initialization phase; and
2) Operational phase.

The flowcharts of the algorithms are shown in Figs. 6 and 7.

The initialization phase involves the use of the supervisory loop and is responsible for building the TPC table and determining the GRPR. It begins by conducting the PRR tests, estimating the SINR values, and fitting the linear approximation to the transmission power and RSSI. Further, the GRPR is computed based on the estimated SINR values. The value of GRPR is used to determine the required transmission power using the abovementioned linear approximation. For each pair of nodes, the transmission power is computed at the receiver and conveyed to the transmitter where the TPC table is stored. During the operational phase, which involves only the use of the regulatory loop, only the received RSSI values are tracked and compared to GRPR, based on which TPC decisions are made. Match the actual power of its transmitted signal to the required transmission power level determined at the receiver. Feedback is expected from the receiver if the RSSI value goes outside GRPR. The transmitter then adjusts the transmission power value accordingly. However, there are limitations imposed by standards and the hardware.

First, there are minimum and maximum ransmission power levels, indicated by the saturation block . Moreover, only limited numbers of discrete power levels are available in the transmitter, dependent on the hardware. The available transmission power level which is nearest to the wanted value is selected.

Transmission power is adjusted on per received packet basis. The update rate will, therefore, vary from milliseconds to seconds depending on the process being monitored or controlled

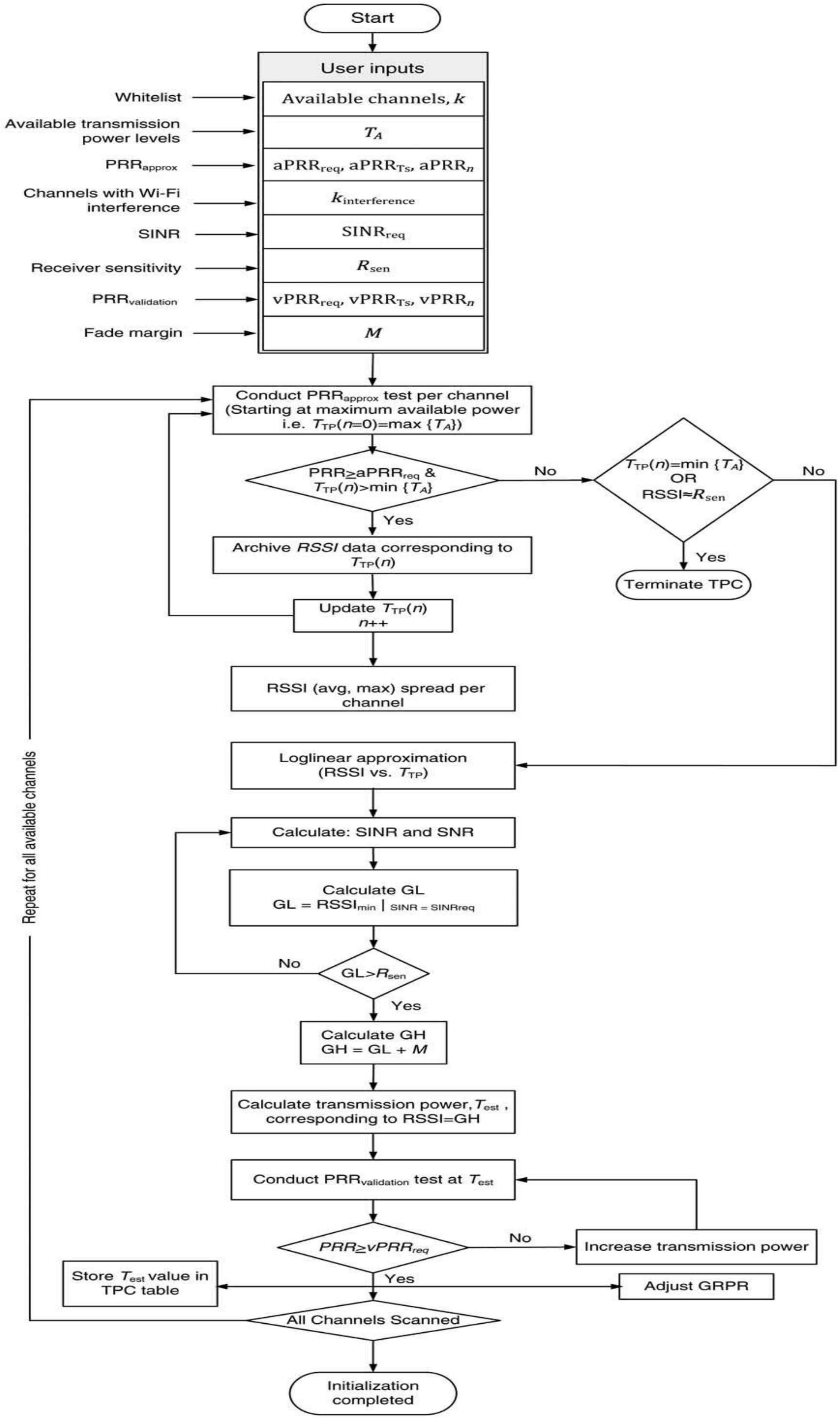

Fig. 2. Flowchart of the initialization phase of the AMC-TPC algorithm

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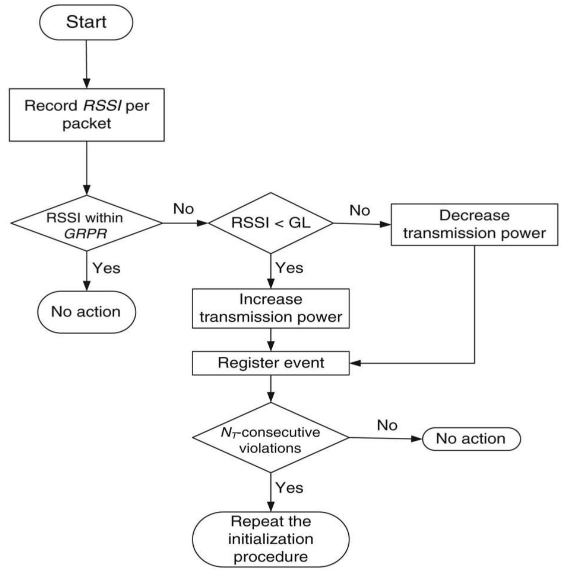

Fig. 3. Flowchart of the operational phase of the AMC-TPC algorithm**.**

V. CONCLUSION

An algorithm has been justified and presented in this paper for TPC for industrial wireless instrumentation. It is based on RSSI and PRR for link estimation. A linear approximation is assumed between the transmission power and RSSI. The algorithm comprises two phases. The initialization phase is responsible for setting the limits of operation for the RSSI values which satisfy the SINR criteria and the fade margin. During the operational phase, the algorithm considers whether the RSSI for the received packets falls within a GRPR. Violation of the GRPR triggers an external feedback loop which adjusts the transmission power.

The practicality and performance of the TPC algorithm were studied through empirical data collected from hardware-in-theloop implementation. The experimental results show that the use of RSSI, PRR, and SINR estimation as proposed in the algorithm offer a good solution for TPC in practical deployments.

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