Ad Hoc Networks 10 (2012) 1267–1277

Contents lists available at SciVerse ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Node localization through physical layer network coding: Bootstrap, security, and accuracy

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ARTICLE INFO

Article history:
Received 12 August 2011
Received in revised form 23 March 2012
Accepted 5 April 2012
Available online 16 April 2012

Keywords:
Physical layer network coding
Node localization
Wireless networks

ABSTRACT

Previous research on physical layer network coding (PNC) focuses on the improvements in bandwidth usage efficiency. Its capability to assist wireless nodes in localization was first discussed in [1]. In that paper, however, the authors discussed only the basic idea to detect and separate the interfered signals for calculating the node positions. Many important issues to turn the idea into a practical approach are not extensively studied. In this paper, we plan to investigate these problems. Specifically, our research focuses on the bootstrap procedures, security, and localization accuracy of the PNC based mechanism. We first study the required node density to bootstrap the localization procedure in both infrastructure-based and self-organized networks. With this question answered, researchers can recognize the network scenarios to which PNC based localization can be applied. We design mechanisms to protect integrity of the exchanged information and defend against node impersonation attacks so that the localization procedures will be robust against malicious activities. For localization accuracy, we study the negative impacts of the position errors of the anchor nodes. We design two mechanisms to reduce the localization inaccuracy for both individual nodes and cumulative procedures through excluding the anchor nodes with positioning errors and introducing multiple bootstrap areas. Both simulation and theoretical analysis are used to support our investigation. This research shows that PNC based node localization can satisfy the security and accuracy requirements of different types of wireless networks and it can be widely deployed.

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1. Introduction

With the proliferation of wireless networks and applications, the localization problem attracts a lot of research efforts. Locating the absolute (or relative) positions of the wireless nodes can improve the performance and safety of the networks. For example, the positions of nodes can be used to authenticate the senders [2], enforce access control [3], and detect Sybil attacks [4]. The position information can also enable the deployment of new location-based services [5–7].

Restricted by the application environments or hardware cost, sometimes we cannot equip every wireless node with the positioning devices such as GPS. Under these conditions, localization algorithms will be adopted. Various range-based and range-free localization algorithms have been designed [8–10]. The adopted techniques include Angle of Arrival [11], Received Signal Strength Indicator [12], Time of Arrival [13,14], Time Difference of Arrival [8,15,16], and Hop-based Reconstruction [17]. Many of these approaches depend on some special hardware to estimate the positions of the nodes. The examples include directional antennas [11], synchronized clocks [18], multiple signal sources [19], power level measurement devices [20], and frequency shift detectors [21]. Although the unit price of the hardware can be very low, the extra cost can still restrict the wide adoption of these methods.

Using the physical layer network coding (PNC) technique to achieve node localization was first studied by Li et al. [1].

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http://dx.doi.org/10.1016/j.adhoc.2012.04.001

PNC uses the additive nature of electromagnetic waves to serve as the coding procedure and improve the network efficiency [22–24]. In [1], the proposed approach determines the position of a wireless node by letting the radio signals from two anchor nodes interfere with each other. The wireless node and another anchor node will capture the interfered sequences. The mechanism will then calculate a hyperbola on which the wireless node resides by comparing the starting points of collisions at the two nodes. When multiple hyperbolas are determined, the wireless node will be positioned at the intersection of these lines.

In their paper [1], Li et al. introduce only the basic idea to detect and recover the interfered signals and calculate the time differences. Many important issues for the practicability and wide adoption of the mechanism, however, are left untouched. For example, since we need multiple independent hyperbolas to determine the position of a wireless node, the density and distribution of anchor nodes will directly impact the number of wireless devices that can be positioned. As another example, the properties that can impact the localization accuracy are not investigated. In this paper, we plan to study these problems. Specifically, our research will focus on the bootstrap procedures, security, and localization accuracy of the PNC based mechanism. We plan to study the required node density for the localization procedures in both infrastructure-based and self-organized networks so that most nodes in the network can be positioned. With this question answered, researchers can recognize the network scenarios to which PNC based localization can be applied. We will design mechanisms to protect integrity of the exchanged packets and defend against node impersonation attacks. For localization accuracy, we will study the impacts of the position errors of the anchor nodes on subsequent operations. The security and localization accuracy results will help end users to determine whether or not this approach will satisfy their requirements. Both simulation and theoretical analysis will be used to support our investigation results.

The contributions of the paper can be summarized as follows: First and most importantly, we conduct a comprehensive study of the practicability of PNC based localization from multiple aspects. The required node density to bootstrap the mechanism and the localization accuracy that can be delivered will help end users to determine whether or not it can be adopted by their applications. Second, while previous research on PNC focuses on its capability to improve bandwidth usage efficiency, the localization mechanism will provide a new incentive for further investigation and wide deployment of this technique. Last but not least, although in this paper we present the bootstrap, security, and accuracy schemes as independent methods, they can be smoothly integrated into a system to improve the overall localization results.

The remainder of the paper is organized as follows: In Section 2 we revisit the basic idea of PNC based node localization. The required anchor node density to bootstrap the localization procedures under different network setups is investigated in Section 3. In Section 4, we study the safety of the approach under different attacks. The localization accuracy is studied in Section 5. Finally, Section 6 concludes the paper.

2. Revisit of PNC based localization

2.1. Introduction to PNC

In this part, we introduce the background of physical layer network coding technique. Fig. 1 illustrates the differences among the traditional approach, network layer network coding, and physical layer network coding. In the topology, A and C depend on B to forward the frames between them. In the traditional approach, A and C need four time slots to exchange a pair of packets. In network layer network coding schemes, node B will conduct an XOR operation (or other operations) to combine *frame*1 and *frame*2. Therefore, three time slots are needed for the operations. In the PNC approach, A and C will send out their packets and B will receive the interference results of the two frames. It will rebroadcast the received signals to both A and C so that they can leverage their knowledge about *frame*1 and *frame*2, respectively to separate the signals and recover the data. From this example, we can see that PNC has the potential to achieve higher bandwidth usage efficiency than network layer network coding. PNC based mechanism does not require the frames to reach the receiver simultaneously since it can accurately locate the starting point of signal collisions [23]. Data transmission using PNC in more complicated network topologies can be found in [23,24].

Since the concept of PNC was proposed in [24], multiple research groups have implemented the approach upon software defined radio (SDR) platforms. In [23], the researchers used the Universal Software Radio Peripheral (USRP) [25] and GNURadio [26] to implement strategic signal-level interference and achieved 500 kb/s bandwidth in the 802.11 frequency range. In [27], the authors implemented multi-relay cooperative communication so that multiple signal sequences from different senders could arrive at the receiver simultaneously. Frequency domain oriented PNC upon the SDR platform was implemented in [28] and significant performance improvements over traditional scheduling and straightforward network coding were achieved. DARPA's Wireless Network after Next (WNaN) program [29] has set a unit cost goal of $500 for a multi-channel SDR device. With the fast development of wireless communication and FPGA techniques, the unit price of the hardware platforms for PNC will become cheaper in the near future.

The PNC technique can co-exist with the traditional wireless communication technique in the same network. It will be transparent to terminals not equipped with corresponding hardware since the devices can identify those interfered sequences through the properties of the received signals. For example, if phase-based modulation is adopted, wireless devices can distinguish among the states of no signal, one signal, and two interfered signals through the perceived power level and its variance [23]. State separation under other signal modulation techniques can be found in [28].

2.2. PNC based node localization

In this part, we introduce the basic idea of using PNC to calculate the position of a wireless node. We use d_{MN} to

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