Multipath Diffuse Routing over Heterogeneous Mesh Networks of Web Devices and Sensors

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Abstract. In this paper we present a new data flow algorithm based on physical diffusion for dense device networks needed for future ubiquitous communications. This diffuse data routing concept is based on multi-path signal propagation aided with adaptive beam-forming methods. Adaptation for beam-forming at different network levels takes place according to physical layer labels given to the devices. This multi-path diffuse routing has the potential to provide low power and resilient communications in dense networks of low cost devices in changing and noisy environments. The main aspects of this diffuse routing concept are illustrated with simulations on a small scale example network.

1 Introduction

The PC era together with the Internet has ushered us into the information-technology age. As this is going on, we are already getting prepared for a post-PC era, enriched with numerous hand-held and intelligent web devices. This brings up issues such as smart environments and proactive computing, utilizing these web devices in a heterogeneous network setting. Such web devices would act as sensors/actuators and could be embedded everywhere in our environment. Communication between these web devices needs to be low power, low cost and resilient to changing and noisy environments. To achieve this, it is highly desirable to have a self-organized autonomous network with ad-hoc multi-hop connections and with multi-path data flows for resilience.

An attractive possibility that can fulfill the requirements listed above can be based on diffusion concepts we experience in our physical environments daily. Initial studies on such diffuse networking concepts have been published recently in [1]. In that work, one assumes that gradients are set between a source/sink node pair in a sensor network. Then, a single best path between these nodes is chosen using these gradients [2]. However, the resiliency of a single path is poor and has to be reinforced regularly by flooding techniques. Therefore, that method has later been extended to include secondary back-up paths which can be activated if the primary path fails [3]. However, this wastes energy due to computations required for the complicated decisions in choosing paths. Furthermore, these prior diffuse networking methods employ conventional medium access (MAC) protocols which are also computation and energy intensive.
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Our work in this report extends these prior diffuse networking studies described above. This is achieved by incorporating multi-path data flows aided by beam-forming concepts. The multi-path data flow incorporates redundancy and therefore increases resilience. The beam-forming provides efficient utilization of energy within the multi-path channel as has been shown by previous studies on space-time coding for wireless communication with antenna arrays [4][5]. In order to increase the energy efficiency further for low-power operation, we propose to bound these multi-path channels within a diffusive data flow region determined by the strength of the signals. These concepts are described below.

2 Diffuse Multi-Path Routing

In this section we describe our concepts on diffuse multi-path routing for a heterogeneous network of web devices. Such a network is schematically shown in fig. 1A. The network sketch in this figure shows a heterogeneous set of devices (black dots) and a variety of connections between them. These devices can be simple sensors and actuators or web devices with any other function. The network links between these devices are also heterogeneous and incorporate technologies such as RF wireless, infrared, fiber-optic, coax, twisted-pair. We envisage that in the future we will have a vast number of these devices and links in an intelligent office or home environment. In order to realize such intelligent environments we must make these devices and their communication links cheap and energy efficient, perhaps even passive. These considerations on cost and energy preclude direct connections from IP-based proxy servers to these vast numbers of devices [6].

Due to the reasons listed in the previous paragraph, and also in line with the reasoning described above, we propose to use diffusion concepts in transporting data between source/sink device pairs. This is shown schematically in fig. 1B depicting a data flow through a multi-path channel between a source and a sink device in a bounded region. As already mentioned above, this region is determined adaptively according to the strength of the signals diffusing around in the network. Using physical diffusion concepts, this region can, for example, be defined by a pair of exponential functions, with each one of the form $e^{-Br/r}$, where $r$ is the distance from a respective device and $B$ is an empirical parameter determined primarily by the distance-bandwidth product of the set of paths connecting to that device. According to this definition, the multi-path channel will be bounded as shown with the shaded region in the figure. All other devices, in between the source/sink pair within the diffuse routing path, act as intelligent transponders adapted to serve as data carriers as efficiently as possible.

As mentioned above, the nodes on the multi-path channel within the data diffusion region help bound this region by beam-forming concepts [4]. In order to achieve this, the internal structure of these nodes should be suitable to realize a space-time filter configuration as indicated in fig. 2. In this figure, the signal is obtained by proper summation of delayed and attenuated versions of the signal arriving at the antenna array. As mentioned above already, the efficiency of multi-path channel utilization is expected to be high with proper space-time coding and subsequent beam-forming using this filter structure. It is highly desirable for the nodes to use only the physical properties of the incoming signals for beam-forming in order to route these signals. In this way, the routing is done at the physical layer rather than the network layer, like in the Internet Protocol (IP) [6], which would require intensive computation, and therefore excessive energy.

3 Network architecture and operation

In previous section, the basic components for an effective operation of dense and heterogeneous web device networks are discussed. This section defines a simple network architecture to simulate and test these basic components; namely the utilization of beam-forming and multi-path data flow concepts towards achieving a diffuse routing algorithm. Such a simple network is shown in fig. 3. Although this network is rather small, it illustrates the basic calculations needed for the operation of diffuse routing. It should be emphasized here, however, that our algorithms have not been extended yet for autonomous operation of a large network. Such extensions require higher layer procedures and will be described in a following publication.

The diffuse routing algorithm, studied in this report, performs multi-path routing paths, act as intelligent transponders adapted to serve as data carriers as efficiently as possible.

Fig. 1. A) The schematic appearance of a heterogeneous web-device network showing a set of devices (black dots) and a variety of connections between them, incorporating technologies such as RF wireless, infrared, fiber-optic, coax, and twisted-pair. B) The expected appearance of the most efficient routes that define the diffuse routing paths (shaded area) between two user devices. All other devices, in between them on the diffuse routing paths, act as intelligent transponders adapted to serve as data carriers as efficiently as possible.
the received signal at the destination is defined by $y$. The antenna signals, $x_j$, are processed by the filter, with tap separation of $T$ and coefficients $w_j$, to get the received signal, $y$. The same filter configuration can also be used to beam-form towards a desired user.

In the example network of fig. 3, the devices can be classified into three types: simple terminal devices, nodes, and passive reflectors. The first classified as 'simple' because their only functions are the transmission of data in the direction of one node and the reception of data from this node, without performing any operations, such as signal separation or equalization. The nodes are more complex, as they are able to do routing, by checking a 'label' attached to each incoming message. In addition, the nodes regenerate the signals, in order to compensate for the noise introduced by the channel. A substantial difference between the simple devices and the other neighboring nodes, in order to separate the incoming signals. This is done by using beacon signals to obtain estimations of the characteristics of the channels. The passive reflectors simply reflect incoming signals, and the direction of the reflection is determined by their position. These reflectors are not shown in the figure, but can be assumed present in some node-to-node or terminal-to-node link, and included in the channel representation.

Here, a brief summary of the procedures needed for multi-path signal processing will be given following ref. [4]. We assume that the data signals originating from terminals (nodes) are given by $u$. After propagation through the multi-path channel and processing by a node's space-time filter, the output signals are

$$y = W_N x = W_N A_{NT} u + n = \hat{u}$$

where $A_{TN}$ is the channel matrix from a terminal to a node; $x$ is the signal at the antenna array; $n$ represents the noise; $W_N = A_{TN}^{-1}$ is the equalization matrix corresponding to the filter structure in fig. 2. Alternatively, if the signals are originating from a node, where we have the choice for pre-equalization, then the received signal at the destination is [5]

$$y = W_N x = W_N A_{NT} u + n = \hat{u}$$

where $W_N A_{NT} = A_{NT}^{-1}$ is the pre-equalization matrix for the channel $A_{NT}$, assuming that the transmitter and receiver arrays have equal number of elements.

4 Network Simulations

The operation of the example network can be split in two parts: adaptation of the neighbors, and data routing.

In the first part, each terminal and each node send a particular sequence, called beacon signal, to all the neighbors in order to train the receivers. Because each node knows these beacon signals, they can estimate the channel impulse response. They separate incoming signals by using an equalization matrix $W$ as discussed in the previous section. This filter is also used in the reverse sense as a pre-equalization filter, in such a way that the network's physical properties take care of the routing. Observe that this filter is present only in the nodes and not in the terminal, because they receive the signal already 'equalized' by the node sender. As there are many more terminal devices than nodes, it is convenient to make them simpler, and consequently cheaper. Nodes use two equalization matrices, in order to simplify upgrading of the network in the case of a new terminal or a new node.

Let us now analyze all the steps in an end-to-end transmission in our simulated example network.

Transmission and coding for simulations: We assume that the data to be sent are QAM symbols. In order to alleviate problems due to multi-path channel, we use Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme [7]. With OFDM the matrix operations get much simpler. In fact, with multi-tone modulation, such as OFDM, it is possible to eliminate the Inter Symbol Interference (ISI) by using a cyclic prefix. Moreover, a large number of frequencies is used in such a way that if some frequency is corrupted by noise, it is possible that the remaining set of frequencies is sufficient for the data flow. For that reason, each device has an OFDM transmitter, and also an OFDM receiver, with exception of the passive reflectors. No channel coding technique is used.
Propagation: The channel impulse responses are represented either by randomly chosen tap values or by Rayleigh fading statistics to incorporate multi-path effects. Furthermore, we also study the operation of our example network with or without noise with Gaussian statistics.

Reception: The reception process discussed here involves only the node. After the OFDM receiver, the signal is a linear combination of data from different users. This signal passes through the pre-equalization filter to separate different user data. The separated data are then processed further for QAM detection with threshold device.

Routing: The diffuse routing algorithm is done at the physical layer. In order to do that, the incoming signal must have some particular property (label), in such a way that the node can determine immediately the destination, without decoding any field in data packets. As OFDM is used, we can use some of the frequencies to represent the label of the signal. We use as many frequencies as the number of the terminals in the example network. In this label the source information is also present. To understand this better, if there are M terminals and N frequencies, with N \( \gg \) M, we choose M frequencies, as shown in fig. 4.

In this way, when a node receives a signal, after separation and equalization, it checks the information in the set of 'identification frequencies' and forwards the signals in the right directions by using the node-side pre-equalization matrix.

Before sending the information to the terminal, the last node has to process all the signals coming from the different directions. This processing compensates for the multi-path effects and also for error detection. After that, the last node sends the data to the right terminal by using the terminal-side filter. To the other terminals that are linked to this node, this signal will appear as noise.

The results of simulations are given in fig. 5, where we also incorporated channel noise. Without channel noise, the received constellation is perfect, and to the other terminal the 'noise' is represented by one point in the origin of the axes. The effect of channel noise will be discussed in more detail below.

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Fig. 4. OFDM frequencies subset showing frequency regions for data signals and user labels

Fig. 5. QAM constellation at the receivers 5 and 6, corresponding to a SNR of 30 dB and 128 frequencies. In this simulation a large number of OFDM symbols is sent from user 3 to user 5. From these figures it is clearly seen that the intended receiver (user 5) gets proper constellation, while its neighbor (user 6) sees only noise.

4.1 Noise in the channels

From fig. 5 it is clear that the constellation at the receivers is not well defined, but there are 'clouds' of points around the QAM values. Depending on the transmission power, these clouds can be big or small, with a consequently big or small degradation of the signal, and a big or small error probability.

We define two types of the error probability:

- **Loss Probability**: this is the probability of loss of one OFDM symbol due to label corruption. The node is not able to recover the destination, and then the symbol is eliminated. This probability depends on M and N. As the ratio M/N decreases, the Loss Probability decreases correspondingly.

- **Symbol Error Rate**: this probability regards the contents of the 'data frequencies' N-M and is independent from those values. It depends on the Signal to Noise Ratio (SNR).

In fig. 6 it can be seen that the probability of message loss is reduced using a multi-path propagation. In our simulations we considered only two possible paths from the first node to the last node, and we used 128 frequencies. The total loss probability is always smaller as compared to a single path propagation, like path 1 or path 2, for any Signal to Noise Ratio value. With this technique it is possible to reduce the transmission power, in order to obtain the same loss probability of a single path propagation. It is also reasonable to imagine that this loss probability can be reduced further using more than two paths.

5 Conclusions

New efficient data communication methods are needed to realize the web devices network infrastructure necessary for intelligent proactive environments of the future. In this report we proposed and described such a data flow concept based on
Fig. 6. Data Loss probability at the last node after a multi-path propagation. 128 frequencies are used and a randomly chosen tap channel is considered. The benefits of multi-path propagation (total) is clear as compared to single path propagation. The high loss values in this plot are due to our choice of very noisy links assumed in paths multi-path diffuse routing algorithm aided with beam-forming. We have demonstrated the operation of this algorithm with a simple example network topology. The simulations with this example network show that the basic physical layer ingredients of this algorithm, such as multi-path data flow, beam-forming and physical label based routing, work successfully. We also discussed the effects of noise in the operation of this data flow method. We now are working to develop extensions to this diffuse algorithm at a higher networking level so that it can be applied autonomously by a large number of web devices in a dense network.

References