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Channel Adjustment for Performance Enhancement in Wireless Networks

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***Abstract*—Channel assignment is essential in wireless communications as it determines which channel to use for each pair of nodes. It has been extensively studied in literature, while all the existing works assume that the link exhibits equivalent performance for different channels and thus the objective is simply to allocate different channels to different wireless links. This assumption is however not always true in practice due to the frequency-selective-fading phenomenon. In this paper, we make a comprehensive study on the impact of the frequency-selective-fading on the network design. Empirical results based on a 21 sensor node testbed and the theoretical analysis reveal the great opportunity for further performance gain by adjusting the channels when traditional channel assignment has been done. We propose a general Channel Adjustment Procedure algorithm and implement it on top of three traditional algorithms, namely PTC, MMSN and TMCP. Trace-driven simulations show that with a simple design, the network connectivity and the energy consumption can be easily improved by 20% with nearly no overhead.**

I. Introduction

Channels are the important resources in wireless communications. Transmitters and receivers should be rendezvoused to the same channel to allow communications, and nearby transmissions in the same channel may cause severe radio interference that impairs the transmission. In the meanwhile, more channels should be employed in parallel so as to obtain a higher network communication capacity. Channel assignment, which determines which channel should be used for each pair of nodes at any time instance, can effectively improve the network capacity and reduce the radio interference.

Channel assignment has been extensively studied in literature [1][2][3]. In conventional channel assignments, the main objective is to reduce radio interference and avoid packet collisions by assigning nearby nodes to non-adjacent channels, so as to increase the utilization of the limited channels. In traditional studies, the networked nodes may have a single (e.g. [3]) or multiple radio interfaces (e.g. [4][5]) which determines the number of channels a node can communicate at a time. And various communication patterns have been considered such as the end-to-end communications in MANETs (e.g. SSCH [2]), and the collection and broadcast in Wireless Sensor Networks (e.g. MMSN [1]).

In all these studies, it is commonly assumed that different channels are equivalent for a pair of nodes. This is, however, not always true in practice. Many theoretical and empirical studies have revealed the frequency-selective-fading phenomenon [6]. It is suggested that a pair of nodes may experience quite different signal strength (and thus the signal-to-noise ratio, SNR) at different frequencies because of the multi-path effect in wireless communications [7].

Frequency-selective-fading has been long considered as a negative factor in communication society because flat SNR for a channel is desired for ease of modulations and demodulations. To successfully transmit, a channel can have only a limited bandwidth (called coherent bandwidth) so that SNR variance in the channel are constrained within a certain range. However we argue that the frequency-selective-fading, or the multi-path effect can also be beneficial.

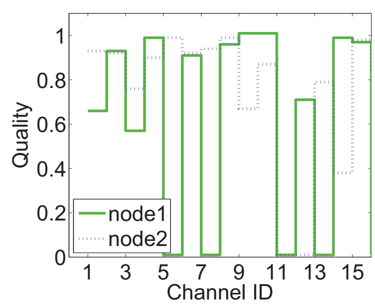

Fig. 1. Link Induced Quality across 80Mhz of 802.15.3 zigbee as measured at two receivers for transmissions from the same transmitter. This figure shows that link qualities of different channels can vary from 0 to 1 and different links prefer different channels

Fig. 1 shows the link quality in terms of packet reception rate (PRR) observed at two receivers for transmission from the same transmitter. The PRRs range from 0 to 1, i.e., from a complete disconnection to a fully reliable link. We call this as Induced Channel Quality (ICQ) for the simplicity of representation. ICQ is mainly caused by the multipath effect. The superposition of phase among different radio propagation paths allow us to conveniently adjust the wireless link quality by setting the link to a different channel. More results about ICQ will be shown in later Sec. II.

ICQ brings great opportunities for network designers to improve the network design. Above the traditional channel assignment, we propose a *Channel Adjustment Procedure* (CAP). In essential CAP identifies the most appropriate channel for a higher network capacity and better connectivity, taking ICQ into account. CAP is designed as a transparent layer. It

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presents an enhanced topology to the network layer under no coordination from the beneath network topology provisioned by the traditional channel assignment algorithms.

CAP not only achieves the collision avoidance in the channel assignment, but also presents a new function that evaluates and considers the link quality variance of changing channels. CAP helps establish a wireless network with higher connected reachability over different paths, thus increase the overall link quality of entire network. Moreover, the link quality is improved with any unnecessary energy costs. In general, it greatly affects the channel assignment method and bring remarkable improvement on top of currently available methods. To validate the effectiveness of CAP, we employ CAP on a topology algorithm PTC which has no channel consideration at origin. We also employ CAP on top of two existing channel algorithms, namely MMSN and TMCP. The essential contributions of this paper are as follows.

1. To the best of our knowledge, we are the first to discover ICQ phenomenon and point out their potential great impacts on the network design. Comprehensive empirical studies as well as theoretical analysis are provided to reveal the physical foundation of these phenomenon. 2. Based on ICQ, we design a simple yet effective CAP for network topology. Above the traditional channel assignment, CAP helps to identify the most appropriate channel for each wireless links so as to optimize the network topology. CAP can be used in a transparent manner. 3. We evaluate the effectiveness of CAP through a large scale of trace-driven simulations. The encouraging results show that compared with no CAP, the network connectivity can be easily improved by 20% in average with nearly no overhead.

The rest of the paper is organized as follows. In Sec. 2, we investigate impacts of channel adjustment for individual links. In the third section, we propose our design of channel adjustment algorithm CAP, and employ it on the existing PTC, MMSN and TMCP algorithm. The evaluation results are provided in subsections of the section 3, it is near to the different CAP designs on different three existing algorithms. The related works will be reviewed in Sec. 4 and we draw the conclusion in the last section.

II. Induced Channel Quality

In this section, we investigate the Induced Channel Quality (ICQ) phenomenon, i.e., the variable link quality according to the changed channel. We will first present our empirical results obtained from a real testbed, and then derive the theoretical foundation for ICQ. In the last part of this section, we will use a set of controlled experiments to verify our theoretical results.

A. Empirical studies

We study the ICQ phenomenon using a wireless sensor network test-bed. The test-bed consists of 20 TelosB nodes [8] which run 802.15.3 zigbee standard [9]. These nodes are deployed in an indoor hall area. A randomly selected node is selected as the transmitter and all the others are deployed within one-hop and act only as the receiver. According to the hardware specification, the current TelosB node supports up 16 channels named as channel 11 to channel 26. The channels start from 2405MHz and each one spans 5Mhz, and thus the central frequency of channels are represented as $f = 2405 + 5 * (k - 11)MHz$, $k = 11, 12, ..., 26$. Then we evaluate the variable link quality with changing channels.

The Fig. 3, 4, 5 are the measured package traces at the channel 11, channel 15, channel 18. There are 100 packages transmitting to 11 receivers which are within all 22 nodes. The lost packages are marked by white bands and the successfully received packages are marked by black bands. At the Fig. 3 as channel 11, node 10 and node 11 lose more packages than they are at Fig. 4 as channel 15. At the Fig. 5 as channel 18, the received packages rate of nodes 6,7,8...11 are at 60 percent lower than at 90 percent as channel 15 at the Fig. 4. From these figures, the empirical trace on testbed shows the link quality value may be different on different channels.

Fig. 6 reflects the link quality variation at the 16 channels for 5 randomly selected nodes. Consider node 1 as a representative node for discussions. When the communication channel is set to 2 or 3, the link quality considerably deteriorates with a connected probability close to 0. However, the connected probability sharply improves to 1 when the channel switches to 10. From this figure, we can conclude that all the 5 nodes exhibit remarkable changes on the link quality when channel ID varies from 11 to 26.

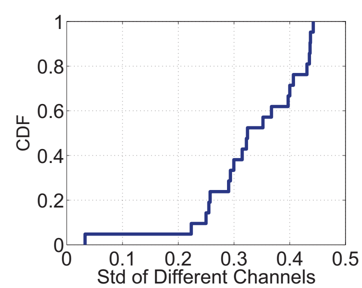

Fig. 2. CDF of the standard deviation of channel quality.

Fig. 2 draws the cdf of the standard deviation (std) of link qualities at the different channels for the 20 receivers. Less than 25% of nodes have the std below 0.25, and over a half of the nodes have the std above 0.3. Considering that PRR is only from 0 to 1, Fig. 2 demonstrates that most nodes have a quite large deviation on the link quality given different channel settings. This first indicates that the link quality might be weak if the channel is not carefully chosen in the conventional channel assignment. On the other hand, it also raises great opportunity for channel adjustment. Besides the traditional channel assignment, we make an adjustment to help the nodes determine which channels should be used, and such adjustment can be done in the transparent manner that in subject to the traditional channel assignment constrains (e.g., nearby nodes should use different channels). We will give our detailed design in later section.

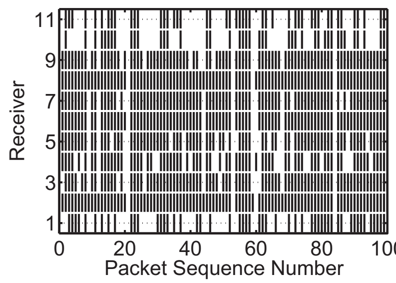

Fig. 3. Traces on channel 11.

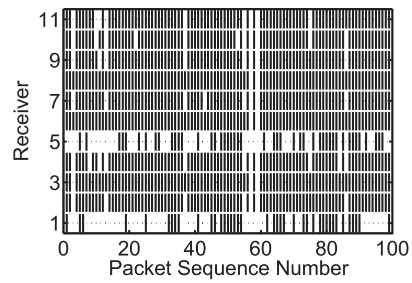

Fig. 4. Traces on channel 15.

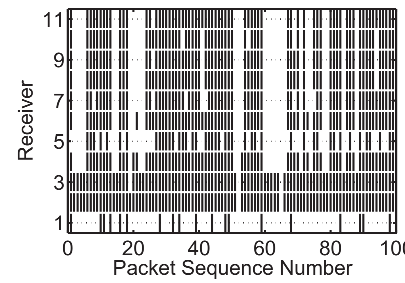

Fig. 5. Traces on channel 18.

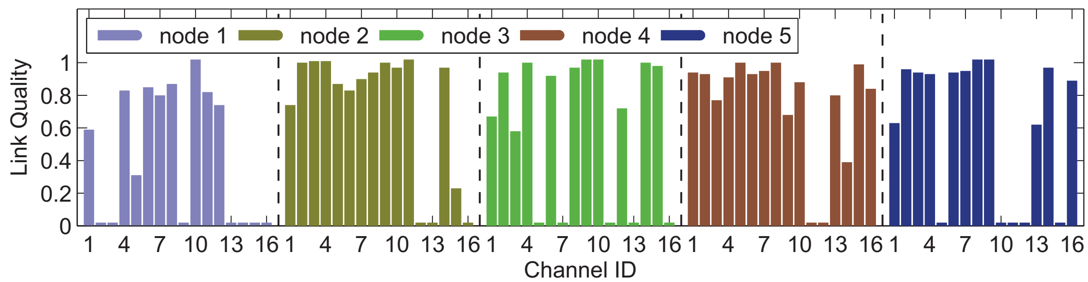

Fig. 6. Link quality versus Channels

B. Theoretical foundation

In this part, we work out the theoretical foundation of ICQ phenomenon. As the link quality is mainly determined by the radio signal strength (RSS), we will derive the relation between RSS and the surround environments of the wireless signals.

ICQ is mainly due to the multi-path effect in wireless communications. When signal transmits from the sender to the receiver, ideally it will spread along the straight line in open space. In practical environments, besides the straight line there can be two or more physical radio propagation paths from the transmitter to the receiver, referred to as multi-path phenomenon. The causes of the multi-path effect are many, such as the atmospheric duct, refraction and reflection. In the indoor environments, the reflections typically occur at the surface of the objects, walls, and the ground. Once reflections/refractions occur, part of signal may transmit to the receiver along the Non-Line-of-Sight (NLoS) path rather than the Line-of-Sight (LoS) path. The NLoS paths between the transmitter and receiver are mainly induced by reflection and refraction and LoS path is the line which connects the transmitter with receiver directly. Radio waves will traverse through all possible physical paths and combine at the receiver.

1) Single path: When there is a single LoS path between the transmitter and receiver, the radio propagations can be modeled by the Friss open space model where the energy field strength is

$$E_{LoS}(t) = \frac{\lambda\sqrt{G_t G_r P_r}}{\sqrt{4\pi}d}\sin(\frac{2\pi c}{\lambda}t + 2\pi\frac{d}{\lambda}) \tag{1}$$

Here G_t is the gain of the sender, G_r is the receiver gain, P_r is the transmission power, λ is the radio wavelength, c is the light speed, d is the LoS path length and t is the time. Replacing all the hardware-dependent parameters by constants, we have

$$E_{LoS}(t) = \frac{\lambda \cdot A_1}{d}\sin(\frac{2\pi A_2}{\lambda}t + 2\pi\frac{d}{\lambda}) \tag{2}$$

where A_1 and A_2 are all constants

2) Multiple paths: Because of the multi-path effect, there can be multiple radio propagation paths between the transmitter and receiver. An NLoS path will introduce the energy field as

$$E_{LoS}(t) = \Gamma\frac{\lambda \cdot A_1}{d}\sin(\frac{2\pi A_2}{\lambda}t + 2\pi\frac{d}{\lambda}) \tag{3}$$

where $\Gamma \in (0, 1)$ is a reflection/refraction coefficient. Equ. (3) can also express LoS path with $\Gamma = 1$.

When signals traverse through the LoS path and the multiple NLoS paths to the receivers, they will combine with the RSS as

$$s(\lambda) = A_1 \cdot \lambda^2 \cdot (\sum_{m=1}^{M}\frac{\Gamma_m}{2d_m^2} + \sum_{m \neq m'}\frac{\Gamma_m\Gamma_{m'}}{d_m d_{m'}}\cos(\frac{d_m - d_{m'}}{\lambda})) \tag{4}$$

where d_m and Γ_m are the m-th path length and reflection coefficient. This is a typical trigonometric function that exhibits periodical properties. It has several periodical part $\cos(\frac{d_m - d_{m'}}{\lambda})$ determined by the two path *length difference* $d_m - d_{m'}$ and the wave length λ.

3) Illustrative example: Consider an illustrative example. The working frequency of TESLOB nodes is from 2.4G to 2.4835G. The signal with 2.4G frequency has a wavelength of 0.125 meters while the wavelength of 2.4835G signal is 0.1208 meters. As indicated at Fig. 7, suppose path lengths

TABLE I
NOTATIONS USED IN THIS PAPER

Notation	Description
$\lambda(u, v)$	Link reachability probability from node u to node v, "link" in the paper means 1-hop link.
$\Lambda_G(u, v)$	Node-pair reachability from node u to v on topology G, which can pass through multi links.
$N_x(u)$	Node u's x-hop neighbor-hood.
$H(u)$	The Channel is set to node u.
$R(u)$	The power level of node u.
T_i	The i-th tmcp subtree.

are $d_a = 2m$ and $d_b = 4.43m$ respectively. For 2.4G signals, the phases of the two paths will be

$$\theta_a = 2\pi(\frac{d_a}{\lambda} - \left\lfloor \frac{d_a}{\lambda} \right\rfloor) = 2\pi(\frac{2}{0.125} - \left\lfloor \frac{2}{0.125} \right\rfloor) = 0$$
$$\theta_b = 2\pi(\frac{4.4374}{0.125} - \left\lfloor \frac{4.4374}{0.125} \right\rfloor) = \pi$$

In other words, the signals from the two paths are completely destructive, which causes a low RSS value at the receiver as Equ.(5). Such a low RSS value will produce a low PRR.

$$(|\sin(\theta_a) + \sin(\theta_b)|^2 + |\cos(\theta_a) + \cos(\theta_b)|^2)^{\frac{1}{2}} = 0 \quad (5)$$

Suppose at another channel the central frequency is 2.4835G, the multi phases become $\theta_a = 0.5\pi$ and $\theta_b = 0.73\pi$. At the receiver end, the RSS will be

$$(|\sin(\theta_a)+\sin(\theta_b)|^2+|\cos(\theta_a)+\cos(\theta_b)|^2)^{\frac{1}{2}} = 1.8714 \quad (6)$$

A simple adjustment of the channel can dramatically affect the link quality.

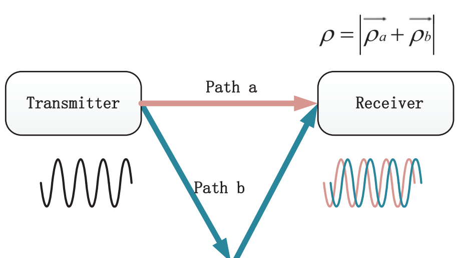

Fig. 7. An illustrative example of phase difference.

III. CHANNEL ADJUSTMENT PROCEDURE

In this section, we take advantage of ICQ to find the adjustable channel assignment in different applications, called Channel Adjustment Procedure(CAP). We show that the overall system performance can be significantly improved without excessive overheads by assigning channels in a precise and controllable way. Table I lists some notations used in this paper.

A. Overview of CAP

The CAP can be mainly described as selecting the best quality with changing channels. The link quality is important in the WSN(wireless sensor network), because it can enhance the reliability of the communications and reduce the transmission times. The CAP method can only solve the quality problem in WSN. If there is an object in WSN having no relationship with quality, the CAP method may have no ability to improve it. But, if the object relates to the quality, the CAP method will improve it without any cost.

We first evaluate the effectiveness of CAP in the channel selection of Probabilistic Topology Control (PTC) [10], in order to achieve a higher connected reachability without redundant power consumption. We then apply this method in MMSN [1] for finding a better channel assignment in the topology that increases the overall link quality. CAP will then be utilized in TMCP [3] to improve the efficiency of packet broadcasting through channel adjustment for reducing the transmission time.

B. Channel Adjustment Procedure with Topology Control

1) PTC: The objective of topology control in WSN is to increase the connectivity of the entire network with lower power consumption [11]. Probabilistic Topology Control (PTC) [10] is introduced to bring a probability model for the description of link connectivity. Given the transmission power of each node, the connectivity probability between any two nodes in the network can be higher than Λ_{th}. The threshold Λ_{th} can be set by users as the network connectivity requirement from the perspective of users. Under this assumption, The fundamental issue of PTC is to seek a balanced tradeoff between the power consumption and the connected probability of the entire network.

Fig. 8 illustrates the workflow of PTC from a node's perspective. Initially, node u measures the link reachability probability $\lambda(u, v)$ to its 1-hop neighbor node v under different transmission powers. Node u sets an initial power $R(u)$. A sink of the network will then estimates the network diameter L. The diameter L is defined as the number of hops in the shortest path between furthest pair of nodes at a topology G_{max}. The G_{max} denotes the topology G when all nodes use the maximal transmission power.

Given a topology G, $\Lambda_G(u, v)$ is the connectivity probability from the node u to node v. If the measured connectivity probability $\Lambda_G(u, v)$ is smaller than the $\sqrt[L]{\Lambda_{th}}$, the node u changes the $R(u)$ as power level to be larger until $\Lambda_G(u, v)$ is larger than the threshold $\sqrt[L]{\Lambda_{th}}$. Every node only needs to make sure the connectivity probability from itself to its any 1-hop neighbor $v \in N_1(u)$ is larger than a threshold $\sqrt[L]{\Lambda_{th}}$. $N_x(u)$ denotes the x-hop neighbor of u. At last, the node u set itself to the $R(u)$ as sending power. PTC algorithm has a derivation network which can ensure the connectivity probability between each pair of nodes is larger than Λ_{th} [10].

In the PTC algorithm, $\Lambda_G(u, v)$ only computes the hop which is lower than 2. It is designed to avoid the repetitive computation of probability of PTC algorithm [10]. We take an example to discuss the calculation of $\Lambda_G(u, v)$ which has

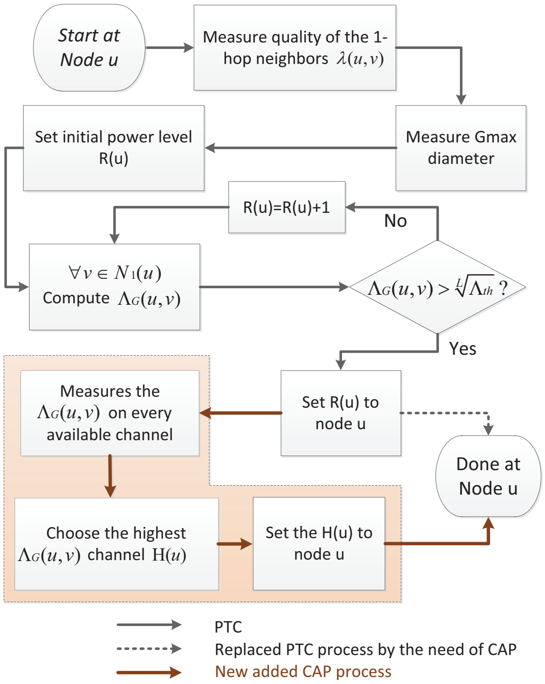

Fig. 8. Flowchart of PTC. The brown arrows and frame represents the CAP processes join PTC. Others arrows and frame reflects the original processes of PTC algorithm.

a 2-hop limitation of PTC. As shown at Fig. 9, the node u is transmitting a packet to its 1-hop neighbor v_1. The blue links which contain the node z is a 3-hop path rather than a hop lower than 2. It will be not used to compute the $\Lambda_G(u, v_1)$. We can obtain the connectivity probability $\Lambda_G(u, v_1)$ as:

$$\begin{aligned}\Lambda_G(u, v_1) =& P((u, v_1) + (u, v_2) \cdot (v_2, v_1)) \\ =& \lambda(u, v_1) + \lambda(u, v_2) \cdot \lambda(v_2, v_1) \\ &- \lambda(u, v_1) \cdot \lambda(u, v_2) \cdot \lambda(v_2, v_1) \qquad (7)\end{aligned}$$

Then the node u will compute $\Lambda_G(u, v_2)$ and $\Lambda_G(u, v_3)$ obeys the same limitation.

After the PTC processes above, the PTC method can achieve that the connectivity probability between any two nodes is larger than Λ_{th}.

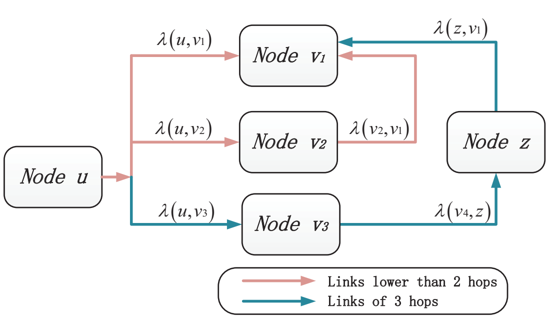

Fig. 9. $\Lambda_G(u, v_1)$ calculation method

2) CAP with PTC: In conventional PTC method, each node should maintain a lowest power level to satisfy the network reachability constraint. In practice, it continuously increases its power level until the connected reachability to its 1-hop neighbors is larger than $\sqrt[L]{\Lambda_{th}}$ [10]. In general, this method achieves the required network reachability in the cost of power consumption. In comparison, our method in CAP is to adjust the channel assignment, so that we can improve the overall connected probability further more by selecting appropriate communication channels. Our method does not involve the cost of power consumption.

As we explained in the previous subsection, the link quality may be strongly related to the transmission channel. So in the PTC algorithm, some simple channel adjustment processes can be added at the tail part of conventional PTC. The link quality in the topology may increases greatly.

As shown at the Fig. 8, joining to the PTC algorithm, the brown arrow and frame are the newly added CAP processes. And the algorithm 1 is a pseudo-code of newly added CAP processes. After the conventional PTC processes, the sending power level $R(u)$ is determined from the node u's perspective. Then at $R(u)$, node u begins to measure the connectivity probability $\Lambda_G(u, v)$ once more. But at this time, it is on the various channels rather than the conventional PTC on single channel. The node u measures and computes the connectivity probability $\Lambda_G(u, v)$ in its 1-hop neighbor-hood. It must be a smallest $\Lambda_G(u, v)$ as it results from every 1-hop neighbor one by one. The node u records the smallest $\Lambda_G(u, v)$ as $\Psi(u, v)$ and forgets others. It is because the smallest probability connection that it is prior to be improved, it spoils the network greatly. We suppose the available channels number of the topology is τ. Then node u repeats the $\Psi(u, v)$ measurement process on each channel k from 1 to τ.

After the above processes, node u records the connectivity probability $\Psi(u, v, 1)$, $\Psi(u, v, 2)$,...,$\Psi(u, v, \tau)$ on each channel k. Then it compares these records with each other and finds out the largest $\Psi(u, v, k)$. The largest $\Psi(u, v, k)$ means the connectivity probability of the smallest 1-hop neighbor on the channel k is larger than it is on other channel. Then the node u finds out the channel k which results in largest $\Psi(u, v, k)$. The node u sets itself to channel k as the transmission channel.

Then we evaluate the effectiveness of applying CAP method into PTC. We use our measurement results in the previous section as the input of trace-driven studies collected from the telosB experiments. Fig. 13 describes the topology of the system of the node density being 100. The evaluation of Fig. 10 and Fig. 11 and some figures in next subsection are operated based on this topology. In the topology, nodes have a transmission range about 20 meters. And they are uniformly distributed over the area of 100*100 meters space. All the traces of topology in this paper are collected from the telosb experiments in the indoor environment.

We suppose that the power level of each node has been set by PTC method. We do not change these power levels of PTC result. Fig. 10 compares the connectivity probability in two different scenarios. The blue circles indicate the

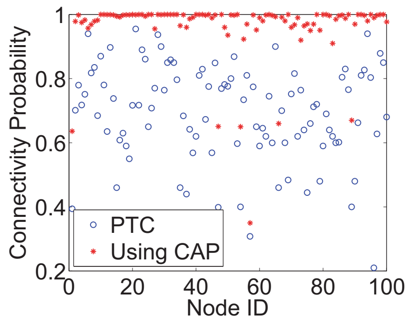

Fig. 10. In PTC, the connectivity improvement through channel adjustment with utilizing CAP.

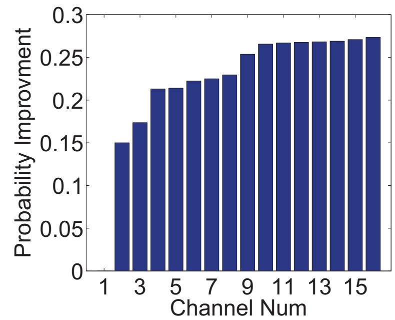

Fig. 11. In PTC, impact of the available channels number with utilizing CAP.

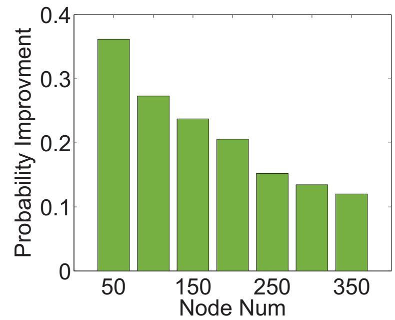

Fig. 12. In PTC, connectivity improvement versus the node density with utilizing CAP.

Algorithm 1 CAP improvement in PTC

Input: τ available channels, $N_2(u)$ topology from the PTC result, $H(N_1(u))$, R(u), node u.

Output: $H(u)$.

The power level of the node u by R(u) $\leftarrow$ PTC result;
Remain other nodes' channels unchanged;
k=1;
%change the transmission channel of the node u;
for $k <$ the number of the available channel τ **do**
  Measure the $\Lambda_G(u, v)$ in the transmission channel k as $\Lambda_{G,k}(u, v)$;
  Compute out $\Psi(u, v, k) = \min_{v \in N_1(x)} \Lambda_{G,k}(u, v)$ value on channel k;
  k=k++;
end for
Compute out $H(u) = arg\max_k \Psi(u, v, k)$;
Set channel $H(u)$ to the node u.

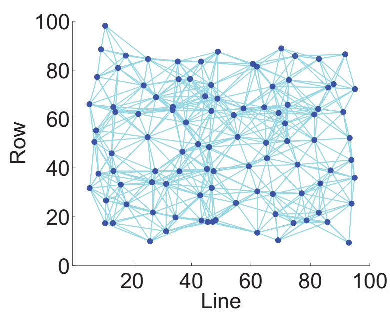

Fig. 13. The system topology has 100 nodes, trace measured from telosb indoor.

worst connectivity probability among all one-hop neighbors of each node when a random channel (channel 11) is selected. The red asterisks denote the worst connectivity probability among all one-hop neighbors after the channel adjustment. The experiment result shows the connectivity probability of majority links among diversified nodes can be enhanced to 1, which clearly demonstrates that the proposed CAP method can improve the performance in a stable manner.

Fig. 11 depicts the connectivity improvement variation under different system capacity. Even though the amount of adjustable channels is not as large as 16 in the experimental systems, the improvement is still significant. From the figure, it is a connectivity probability increase of 0.27 at only 9 channels provided.

Fig. 12 varies the node density in the entire topology from 50 to 300. As we can expect, the quality is greatly improved when nodes are relatively sparsely distributed. It is because the beginning connectivity is higher at a dense deployment than at a sparse deployment. Then the space can be promoted to the dense one is lower than the sparse one. From the Figure, we can see the improvement starts to decline when there is a dense deployment of nodes.

Our trace-driven simulation has proven that the channel adjustment can greatly improve the overall reachability by changing the one-hop connectivity.

C. Channel Adjustment Procedure with MMSN

1) MMSN: The frequency assignment in wireless network can help alleviate the channel collision problem by coordinating the channel utilization among neighboring nodes. Among all existing solutions, MMSN algorithm is a distribution algorithm, every node only monitors its 2-hop neighbor information and decides its own receiving channels setting [1]. And based on these assigned channel, nodes can communicate to each other on the known receiving channels.

Fig. 17 illustrates the workflow of MMSN from the perspective of node u. To achieve the channel assignment, node u first exchanges their IDs among two communication hops. After this step, node u compares these IDs with the ID of itself. If the ID of node u is the smallest one in its 2-hop neighbors, the node u sets the smallest available channel to itself and finishs the channel assignment. If else, the node u monitors the nodes which have lower ID than itself. The node u begins to wait until all the nodes with lower IDs have be assigned channels. After they all be assigned channels, the node u sets the smallest available channel to itself and makes sure the channel assigned is unique in its 2-top neighbors. After a channel is assigned to the node u, node u informs its 2-hop neighbors about its new channel information. Then the MMSN algorithm is done at the node u.

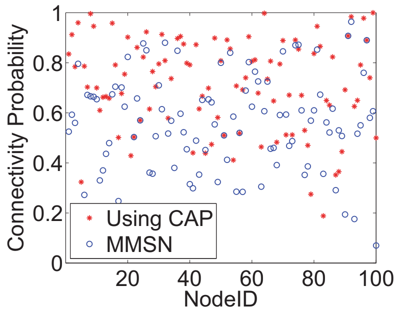

Fig. 14. In MMSN, improvement of different channel adjustment with utilizing CAP.

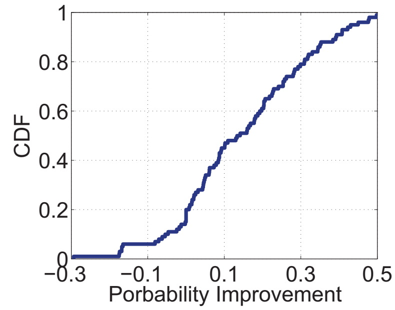

Fig. 15. In MMSN, CDF of links probability improvements with utilizing CAP.

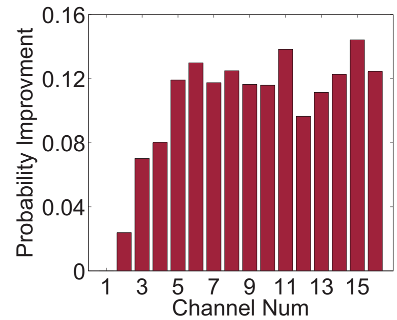

Fig. 16. In MMSN, the impact of available channel number with utilizing CAP.

The others part of the paper [1] mainly discuss how to use assigned channel to send packages. The main idea of it, if node u wants to transmit a package to 1-hop neighbor node v, it needs to know the receiving channel of node v and transmits packages on it.

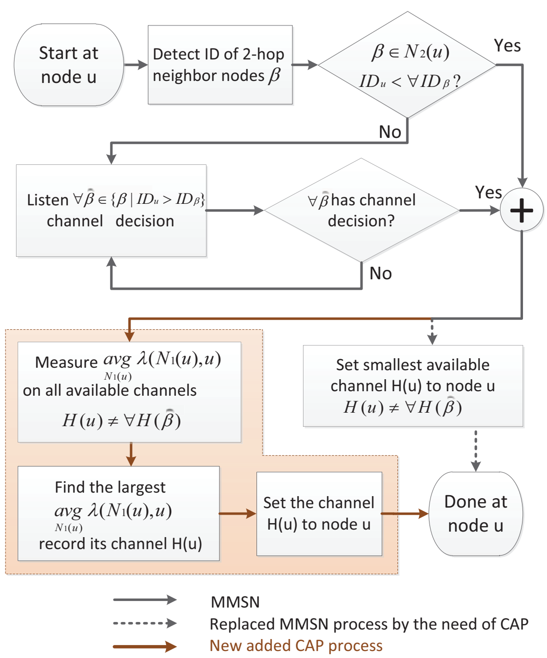

Fig. 17. Flowchart of MMSN. The brown arrows and frame represents the CAP processes join PTC. Others arrows and frame reflects the original processes of MMSN algorithm.

2) CAP with MMSN: Some experimental results in the previous section have revealed that the link quality is closely associated with the channel selection. To improve the link quality in practice, it would be beneficial to include this consideration in the channel assignment. For comparison, we only conduct the channel adjustment based on the process of MMSN method, rather than sophisticatedly reformulate the channel assignment as a global optimization problem using experimental results.

In MMSN method, the node with the smallest ID value always chooses the smallest available frequency. In comparison, our channel adjustment method assigns the channel which results in an optimal link quality to the node. As shown at the Fig. 17, joining to the MMSN algorithm, the brown arrow and frame are the newly added CAP processes. And the algorithm 2 is a pseudo-code of newly added CAP.

From the perspective of node u, the channel assignment of MMSN is only receiving channel of the node u. The node u measures the link quality probability $\lambda(N_1(u), u)$ from its 1-hop neighbor-hood to itself. It computes average value of these $\lambda_k(N_1(u), u)$ which comes from all 1-hop neighbors of node u. The node u records the result as $\underset{N_1(u)}{avg}\ \lambda(N_1(u), u)$. Suppose the available channels number is τ, the node u measures the $a_k = \underset{N_1(u)}{avg}\ \lambda_k(N_1(u), u)$ on each channel k from 1 to τ. After the node u gets all the average values as a_1,a_2...a_τ, it compares them with each other. Then the node u finds out the channel k which results in largest a_k. The node u sets the channel k to itself as $H(u)$.

The optimality here denotes that the average transmission quality from all of one-hop neighbors to the node reaches an optimal value. Meanwhile, the order of channel assignment remains the same as the MMSN method. Eventually, our channel adjustment not only guarantees the same objective of collision avoidance as MMSN method, but also achieves an improved link quality in the topology.

Then we conduct simulation studies based on the telosB trace and topology which are same as the trace and topology in PTC subsection at Fig. 13.

Fig. 14 reflects the average reachability variation after we join CAP method to MMSN method. The blue circles indicate the receiving connectivity probability of each node when MMSN channel assignment method is selected. The red asterisks denote the connectivity probability of each node when CAP channel adjustment method join. We can observe that red nodes occupy the upper half of the figure, which indicates that the connected probabilities for most of existing nodes are raised to a higher level. This trend can be precisely captured after we plot the Cumulative Density Function (CDF) of channel quality improvement in Fig. 15. Although 10% of nodes have a slightly decreased link quality due to the

Algorithm 2 CAP improvement in MMSN

Input: node u, $N_1(u)$ ID, $N_2(u)$ ID, τ available channels;
Output: the channel node u get assigned $H(u)$;
set channel $k = 1$;
for $k <$ the number of available channel τ **do**
  measure the quality $\lambda_k(N_1(u), u)$ which is from 1-hop neighbors $N_1(u)$ to node u;
  compute the average of these quality values as $a_k = \underset{N_1(u)}{avg}\ \lambda_k(N_1(u), u)$ on channel k;
  $k = k++$;
end for
compute $H(u) = \underset{k}{arg\max}\ a_k$;
Set $H(u)$ to the node u.

random nature of the channel assignment order, most nodes can still benefit from the channel adjustment with 10% to 40% connectivity probability improvement.

Then we discuss the impact of available channel numbers in Fig. 16. At this figure, the channel quality improvement is defined by the average quality improvement in 100 nodes, which includes the few "negative improvement". The channel quality improvement stably increases when the amount of adjustable channels varies from 1 to 5. The difference of reachability between the MMSN and MMSN with CAP then maintains around 12% when there is a larger space for the adjustment.

D. Channel Adjustment Procedure with TMCP

In conventional channel assignment methods, nodes typically use different channels for downstream and upstream communications. Thus nodes have to switch their channels in order to receive and transmit packages in a multi-hop flow. However, the frequent channel switching can induce to the loss of packets. TMCP [3] is proposed to resolve this issue, which is a tree-based multi-channel protocol for data collection applications.

1) TMCP: Fig. 18 illustrates the workflow of TMCP. Using BFS-fat tree algorithm [12], the network constructs a fat tree based on root r. According to the available channel number τ, the BFS-fat tree will be divided to some smaller subtrees T_k. And the T_k must be connected to the root node directly. Different subtrees T_k have channel isolation. It is designed to avoid the interference among different subtrees. Then the next step of the TMCP algorithm mainly reduces the inter-tree interference by every node deciding itself to join one subtree.

Begin at the BFS-fat tree $level = 1$, each node will be sorted in ascending order by the parents' number. It is because the nodes with fewer parents are less free to choose channels. In the sorted list, nodes try to join each subtrees T_k and compute the interference to the subtrees T_k as it brings. Nodes will select to join a subtree T_k to which they bring the lowest interference. This process is the inter-tree interference reducing method of the TMCP. Then at the same processes,

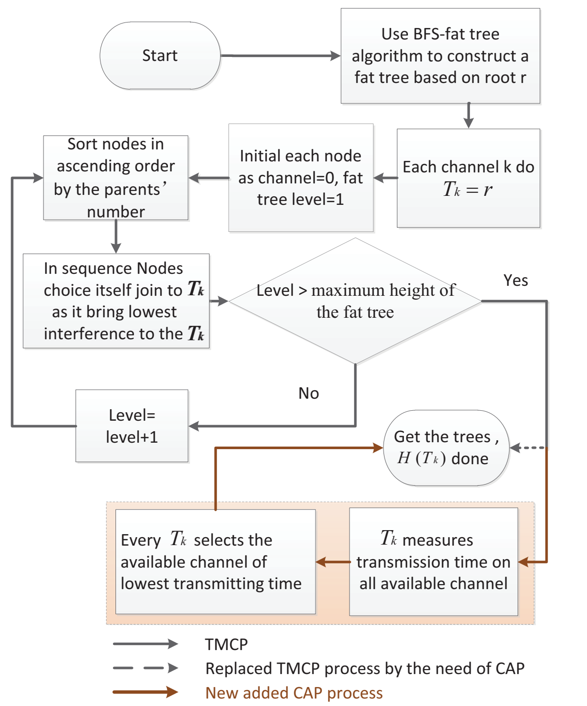

Fig. 18. Flowchart of TMCP. The brown arrows and frame represents the CAP processes join TMCP. Other arrows and frame reflects the original processes of TMCP algorithm.

at level=2,3... nodes will select a subtree to join in until the level is higher than the maximum height of the fat tree.

After the above processes, the BFS-fat tree is divided to many subtrees which has different and unique channels as Fig. 19. The root sink node is the gray node which connects to three subtrees indicated by different colors.

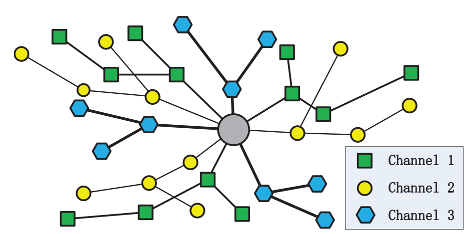

Fig. 19. TMCP subtrees.

Then the interference among subtrees can be eliminated by assigning different channels. Within a subtree, nodes communicate to each other via the assigned channel, which reduces the frequent channel switching as compared to the traditional method. And the inter-tree interference can be weaken since every node selects a lowest interference subtree to join in. TMCP method can thus achieve the aim of channel assignment in the WSN by reducing the package loss rate and some experiments can prove it [3].

2) CAP with TMCP: TMCP can achieve high efficiency in the channel assignment by formulating a multi-tree topology.

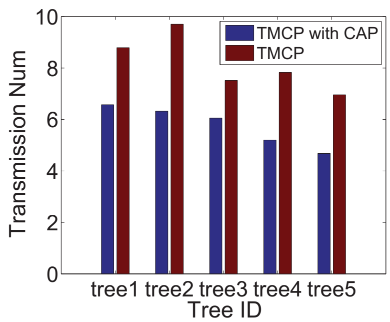

Fig. 20. In TMCP, the improvement with utilizing CAP.

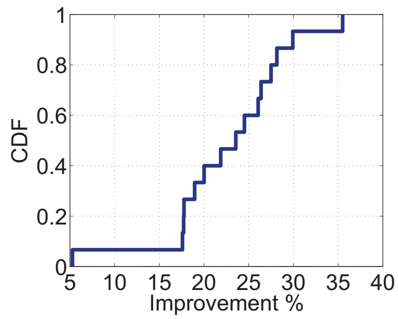

Fig. 21. In TMCP, CDF of improvement with utilizing CAP.

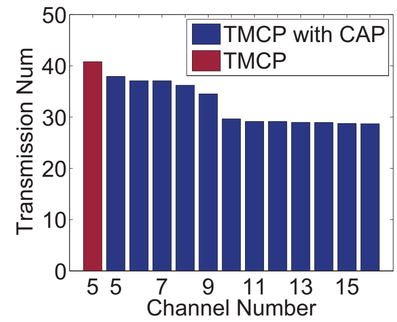

Fig. 22. In TMCP, the impact of the available channel number with utilizing CAP.

However, channels are still randomly assigned to different trees in TMCP. From above applications improved by CAP method, we can observe that the overall performance of the network varies significantly when channels are allocated in different ways. Thus, we also attempt to introduce CAP method in TMCP by selecting the most appropriate channels for different trees. The construction of the tree topology in our mechanism remains the same as the procedure described in TMCP method. Our CAP optimization objective in channel assignment is to minimize the expectation of the total number of transmissions across different trees.

As shown at the Fig. 18. Joining to the TMCP algorithm, the brown arrow and frame are the new added CAP method. And the algorithm 3 is a pseudo-code of new added CAP which added at the tail of the original TMCP. We sort the trees T_i in ascending order by the number of node, beacause subtrees with more nodes are prior to be assigned channel. Then we got a sorted tree list besides the sorted node list which is built by TMCP method. We suppose the system has an available channel number τ. In the sorted tree list, the subtrees T_i explore their optimal channel k from available channels which results in minimum expectation of transmission times Equ.(9)(10) one by one. And subtrees set the optimal channel as $H(T_i)$ to themselves. At this process, the assigned channel will be removed from the available channel set, it can make sure every subtree has an unique channel. Eventually, the expectation of the number of transmissions is reduced without excessive cost.

The expectation of transmission time calculation is based on the link quality from the branch node to the leaf nodes. For example, there are three leaf nodes l_1,l_2,l_3 and a branch node u. The probability that at transmission time $\varepsilon(u)$ still exists at least one leaf node receive no package is:

$$P(\varepsilon(u) > s) = P(\overline{l_1}^s \cup \overline{l_2}^s \cup \overline{l_3}^s) \tag{8}$$

And the expectation of transmission times can be computed by

$$\begin{aligned} &P(\varepsilon(u) > s-1) = P(\overline{l_1}^{s-1} \cup \overline{l_2}^{s-1} \cup \overline{l_3}^{s-1}) \\ &P(\varepsilon(u) = s) = P(\varepsilon(u) > s-1) - P(\varepsilon(u) > s) \\ &Exp[\varepsilon(u)] = \sum_{k=1}^{+\infty} s \cdot P(\varepsilon(u) = s) \\ &\quad = \sum_{i=1}^{3} \frac{1}{1-P(\overline{l_i})} - \sum_{i \neq j} \frac{1}{1-P(\overline{l_i}) \times P(\overline{l_j})} \\ &\quad + \frac{1}{1-P(\overline{l_1}) \times P(\overline{l_2}) \times P(\overline{l_3})} \end{aligned} \tag{9}$$

If there is n leaf nodes, the expectation of transmission times can be computed by

$$\begin{aligned} Exp[\varepsilon(u)] &= \sum_{i=1}^{n} \frac{1}{1-P(\overline{l_i})} - \sum_{i \neq j} \frac{1}{1-P(\overline{l_i}) \times P(\overline{l_j})} \\ &+ \sum_{i \neq j \neq e} \frac{1}{1-P(\overline{l_i}) \times P(\overline{l_j}) \times P(\overline{l_e})} + ... \\ &+ \sum_{i \neq j \neq e \neq ...} \frac{1}{1-\underbrace{P(\overline{l_i}) \times P(\overline{l_j}) \times P(\overline{l_e}) \times ...}_{n}} \end{aligned} \tag{10}$$

Computing this transmission times at every branch node and summing them with each other, we can get transmission times I_j on whole TMCP tree.

We then examine the effectiveness of our adjustment strategy with CAP based on the experimental results collected in the previous section. There are in total 5 subtrees linked to the sink node in our simulation setup. Each subtree in total contains 10 to 15 nodes and the maximum out-degree is 4.

We plot the expectation of the number of transmissions over different trees in Fig. 20 given a generated topology. All 5 subtrees require less amount of transmissions to complete the packet broadcasting after we apply CAP method, and the improvement varies from 20% to 40% depending on the specific subtree. This clearly demonstrates the improvement of overall reachability in the broadcasting scenario in which the channel selection is affected by a large amount of links in each subtree.

To further investigate the overall impact of channel adjustment to TMCP method, we generate 15 different topologies

Algorithm 3 CAP improvement in TMCP

Input: τ available channels, trees T_k result from TMCP;
Output: channels $H(T_i)$ assigns to the trees T_i;

Tree_list= $\{T_k\}$.
Available_channel_list =$\{1, 2...\tau\}$.
Sort the trees T_i in ascending order by the number of node.
i=1.
for $i <$ the number of the tree number **do**
  j=1.
  for $j <$ the available channel number **do**
    Compute the transmission time $\mathrm{I_j}$ of Tree_list(i) on channel Available_channel_list(j). j=j++.
    j=j++.
  end for
  Compute out the $j = arg\min_j\ I_j$.
  Set channel Available_channel_list(j) to the $Tree\_list(i)$ as $H(T_i)$.
  The list of available channel removes $H(Tree\_list(i))$.
  i=i++.
end for

and compare the effect of two mechanisms in Fig. 21. The CDF function of performance improvement indicates that the reduction of transfer times brought by CAP method is not fixed. The improvement is between 20% to 30% in most scenarios which is satisfied in practice. Meanwhile, the degree of improvement is also related to the number of channels as shown in Fig. 22. Observations demonstrate that a set of 10 available channels should meet the demand of improving TMCP method through effective channel adjustment.

IV. Related Work

To avoid the potential channel collision in WSN, the channel assignment has been long discussed in the literature. For instance, [2] sets up a time table for each channel, in order to dynamically control the channel utilization of participating nodes. [1] assigns channels on a two-hop neighborhood basis, and uses the time-slotted mechanism for the transmission control. [3] considers a data collection and distribution system, which divides all nodes into multiple disjoint trees with unique channels. However, above channel assignment methods commonly assume that channels are equivalent, which ignores the distinct quality of different channels. Our works explore the theoretical foundation of link quality variation, and focus on assigning channels in a more appropriate way that flexibly adjusts the link quality.

The principles of our works have been discussed in the field of wireless communications in a different perspective. A model for communication systems has been built in [13], which observes that the frequency response of the signal in a multi-path environment cyclically fluctuates. This phenomenon is defined as "Frequency Selective Fading" in the field of communications. If the frequency of the signal is selectively fading within the selected band, then the signal distortion leads to an intolerable bit error rate at the receiver side.

V. Conclusion

Channels are commonly assumed to be equivalent in all existing channel assignment studies, which are not always true in practice. In this paper, we conduct extensive measurements to explore the relation between the communication channel and the link quality. Experiment results indicates that the link quality is closely associated with the selected frequency, defined as ICQ. Theoretical analysis on our observations indicates that the phenomenon is mainly caused by the multi-path effect. We can take advantage of ICQ to benefit the performance of WSN applications. Trace-driven simulations on three representative applications prove the effectiveness of the proposed channel adjustment procedure, by achieving remarkable performance improvement with minimum overheads.

VI. Acknowledgement

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