Cross-layer Optimization, Especially Combination of Channel Estimation and Position Determination in Multihop Wireless Networks (Cellular and Adhoc)

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Abstract— **The key concern of our research is to investigate concepts ensuring an integration of information and processes available at the layers 1 up to 3 of the protocol stack to realize an overall optimization of both resource usage efficiency and performance in self-configurable and self-healing wireless networks (cellular and adhoc). The essence of the research avenue lies in the fact that, from an information theoretical point of view, information available at different layers of the protocol stack contains per se a certain degree of redundancy that can be used for cross layer optimization. For example, processes of the physical and MAC layers like directional channel estimation, synchronization, bit error rate and signal strength can be used to obtain a quite good estimation of the range (distance) between senders and receivers. On the other hand, position and topology information, for example, can be used to optimize a series of processes at the other layers, for example, channel estimation & adaptive modulation, power control, and mobility management (including movement detection, dynamic guard channel schemes, handoff and load balancing).**

Keywords— **Cross-layer optimization, integration of positioning in the communication process, channel pridiction and adaptive modulation.**

I. Introduction

The optimization of resource usage especially on the air interface (the air interface is, as is generally known, the bottleneck concerning available bandwidth in mobile communication networks) for mobile networks is a critical issue. A series of resource management approaches have been developed in the last years, which perform more or less an interaction between MAC, network and transport layers of the communication protocol stack [1, 2]. It is evident that this cross-layer interaction opens up a significant optimization potential. However, the reachable improvement has a certain upper bound. Further, we should notice that the cross-layer optimization approaches published up to now do not involve the physical layer. Though all expectable significant enhancement of the available bandwidth on the air interface can only be reached by improving the spectral efficiency at physical layer.

This leads us to the focus of this paper. We do screen all the upper layers of the protocol stack (that is, from MAC layer to transport layer), searching for data and processes that can be used in a feedback fashion to optimize processes at the physical layer. Generally, at physical layer all processes use knowledge available on a per-link basis. There is generally no involvement of knowledge available on a network-wide basis. The result of our screening is that position information is, amongst others, a key asset that can be used to optimize a series of processes of the physical layer, especially the following: channel estimation, synchronization, (adaptive) modulation. The more accurate the position information is, the higher will be the impact of its involvement in the optimization of processes at physical layer. The position information we refer to is not only the position of a single node, but, to be general, the overall geographical information of either a portion of the network or of the whole network. Besides, whenever velocity information is additionally available, a prediction of the topology can also be of precious use in the mentioned optimization processes. In Section III we shortly demonstrate that this is feasible.

It is true that accurate position information can be of great use in the optimization of processes at the physical layer. However, how should we generate that accurate position information? In the last years, satellite-based positioning systems (e.g. GPS) have been seen as a global infrastructure for positioning. GPS positioning is in fact actually used in many networking applications, not only for position and velocity determination, but also for time synchronization. Satellite-based positioning has however a series of limitations:

- low availability of navigation signals in certain environments (outdoor urban ($< 50\%$) and indoor ($\approx 50\%$));
- necessity of a GPS-interface at all nodes, which has an significant impact on the energy consumption (this can be critical for a series of applications like sensor

networks, where the energy budget is a very limited and sensitive resource);
• the reachable accuracy is, depending on the application, not good enough;
• the so-called TTF (time-to-fix), that is, the time needed for a position calculation, which is in the range of 10 s up to some minutes, can be too long for some applications.

An alternative to Satellite-based positioning is positioning based on cellular networks. This has however similar limitations as the one described above. Especially the low accuracy (in the range of 100 m) and the relative high TTF (order of 10 s) make this type of positioning to be inadequate for an involvement in the optimization of processes of the physical layer, where time horizons in the order of some 100 ms should be required. Besides, positioning based on cellular networks is generally expensive in term of signaling load.

Because of all these reasons amongst others, especially in networking scenarios where the use of position information is critical and intensive (e.g. a certain type of wireless adhoc and sensor networks), new concepts of the so-called ad-hoc positioning are being developed, see Refs [3-4]. Some of them partly use GPS in some of the nodes, whereby newer proposals are GPS-free, i.e., they try to generate the position information without the assistance of any external positioning infrastructure [5-7].

Ad-hoc positioning points out, from our point of view, in the good direction, namely the integration of the position determination function in the communication process. Hereby there are two possible approaches. The first one can consist in using and/or involving part of the available network resources (wheresoever in the protocol stack). This approach has the disadvantage that the position generation process will appear as a kind of additional overhead in the overall communication process. A second approach, which is the best and the one we favor and pursue, should consist in generating the position information as a spin-off product by primarily using data and processes that are anyway part of the normal communication process. So doing, one rather obtain an improvement of the overall network efficiency.

Now, we should have a look at the mechanisms that should be involved in the generation of the position information. Basically, there are two steps: estimation of ranges to more than one other node; performing of a triangulation to calculate the position out of the individual range estimation. Therefore, range estimation between two nodes is the basic function in the whole position determination process. Then follows the distribution of the position information in the network to generate a topology information. The distribution and the warehousing of the position & topology information can be performed using a form of distributed location server architecture (see for example GLS [8]).

In Section II we show how the generation of the positioning information can be integrated in the normal communication process. Of particular importance are processes at physical layer that will generate range and relative velocity estimations, with the highest accuracy, on a per-link basis as a spin-off. Other processes and data at MAC layer will also be involved although their contribution is of less accuracy. However, the fusion of redundant information from different data and layers that have a certain correlation to the range between sender and receiver ensures a robust positioning and opens ways to develop adaptive filter mechanisms to cope with a series of errors like the well known "non-line of sight problem"[9]. The distribution of the position information as such will be embedded in signaling processes at MAC and transport layers.

After discussing in Section II ways of how to involve processes of the physical and MAC layers in the generation of an accurate and robust position information, Section III focuses on approaches that involve the position & topology information in the optimization of a series of key processes of the physical layer. The expected result is an improvement of the overall spectral efficiency amongst other things. The involvement of the position information in processes of the MAC and network layers can, just to give an example, result in, amongst other things, an improvement of both throughput and overall power consumption.

Finally, Section IV summarizes a series of concluding remarks and an outlook.

II. Consider positioning and topology determination

The position determination process is graphically summarized in Fig. 1. The key issues related to position determination are: estimating (pseudo)ranges; determining relative velocity between sender and receiver; determining the time of applicability for the range estimations; and computing the position of the receiving antenna using the range estimations and timing information. The range and velocity estimation uses following data and resources for range and velocity estimation: channel estimation, synchronization, Doppler effect related data, bit error rate, signal strength, and signaling at layers 2 and 3. A local distribution of the range and velocity estimations is necessary for a series of processes involved in the position determination and the eventual correction of related errors: triangulation, Kalman filtering [10] and correction of the NLOS (non-line of sight) problem. Concerning the correction of the NLOS, we extend the approach of Ref [9] by involving knowledge about the velocity information, Kalman filtering and we adapt it especially to the context of an adhoc positioning (note that the concept of Ref [9] has been developed for a cellular positioning context).

The distribution of both position and velocity information provides a basis for a reliable topology evolution prediction. This can be realized by a distributed location server architecture. Of particular interest is that we also pursue the integration of a time synchronization in the topology determination & prediction processes. For this, the concepts of Ref [8] must be accordingly extended or reformulated.

Besides, position and topology information are used to optimize following processes amongst others: channel estimation and adaptive modulation; movement detection & soft handoff for real-time traffic; dynamic guard channel schemes; mobility domain and cluster management, and a two-layer power control in the frame of power-and-position aware MAC, Routing and handoff in multichannel wireless systems. Thus, there is a huge potential to optimize a series of approaches similar, for example, to the ones addressed in Refs [11-13].

In this section we have just described the different issues and tasks that should be the focus of research on this field. For most of the issues described above adequate algorithms are being developed, which will be evaluated, fine-tuned and validated by both extensive simulations and labor measurements (and test beds).

III. Consider channel estimation and other processes at physical layer

For coherent communication systems, the channel must be estimated in order to reconstruct the received signal [14]. We consider the general case of directional channel estimation. The channel parameters to be estimated are the channel impulse response (CIR) and the arrival angle of each path. The estimated channel impulse response consists of several taps. Each tap corresponds to a transmission route and the corresponding propagation delay. Under the assumption that receiver and transmitter are perfectly synchronized, the propagation delay reveals the length of the corresponding path.

The tap with the shortest propagation delay relates to the shortest transmission route. If this route is the line of sight (LoS) connection between the receiver and the transmitter, then the length of this transmission route is the distance between the receiver and the transmitter. From this point of view, one can state that the distance between the transmitter and the receiver can be calculated on the basis of the estimated channel. If we use not only the information of the shortest tap, but also the whole information of all taps including the channel coefficients, the time delay, and the arrival angle, then this information describes a signature associated to the location of the receiver. This concept is illustrated in Fig. 2. It is obvious that in each location the channel parameters are different. Therefore, these channel parameters give a good basis for position determination. For example, when the arrival angles of the transmitted signals to the receivers are known at different times, the movement direction of the receiver can be detected. Moreover, the maximal Doppler frequency f_D can be evaluated from the estimated channel [15]. This information helps us to determine the relative velocity between the receiver and the transmitter.

When the location and the movement of the receiver as well as the range of the transmission environment can be estimated, the next location of the receiver can be predicted. It follows that the next channel state at a time in a near future can also predicted. The channel state prediction at a next time in the near future is a challenging task that will require the developement of adequate algorithms. This predicted information, such as the predicted channel, is very useful for the optimation of processes like adaptive modulation, and power control. This information can also be used to improve the performance of the channel estimation. The combination scheme is described in Fig. 3 and can be explained as follows. We observe the system at two different points of time t_1 and t_2 with the time observation window $\Delta t = t_2 - t_1$. We assume that at time t_1 the estimated channel is $h(\tau, \alpha)|_{t=t_1}$ as shown in Fig. 2, where τ is the time delay and α is the arrival angle. Both of them are funtion of the time t. The information from the channel estimation at a time t_1 together with the synchronization information are used for position determination as pointed in Fig. 3. The predicted channel state information for the next time t_2 can be obtained based on position and velocity information.

For adaptive modulation, the appropriated modulation scheme will be selected according to predicted channel state. We define the channel state to be in a bad condition, if at this time the signal to noise ratio (SNR) is low. This is the cases, when the channel suffers from a deep fading. In other cases, the channel state is in a good condition. If the predicted channel state is in bad condition, then in the next time a low modulation level should be used. But, if the predicted channel state of the next location is in a good condition, a higher M-ary modulation scheme can be used [16]. By using adaptive modulation, the spectral efficiency can be improved. Similarly, the information of the predicted channel can be applied to power control. That is, we know previously how to regulate the transmitted power in accordance to the information of the predicted channel.

The predicted channel can also be used to improve the performance of the current measurement results of the channel coefficients. This process is very similar, in the essence, to what is realized in the Kalman-filtering [17]. There are, however, differences due to the nature of the complex physical processes involved here. This consideration can be illustrated in Fig. 4, where $h^*(\tau,\alpha)|_{t=t_2}$, $h(\tau,\alpha)|_{t=t_2}$, $h^{\mathrm{opt}}(\tau,\alpha)|_{t=t_2}$ are respectively the predicted channel, the actual measured channel, and the final estimated channel coefficient. The channel estimation at a time t_2 will be improved by a scheme comparing the actual channel estimation and the predicted one, whereby the prediction involves the following knowledge: previous channel estimation, position and relative velocity information, and the actual channel information.

IV. Conclusions

This paper has described a clear vision that open news ways for cross-layer optimization, whereby the position information plays an important role. One sees a clear synergy effect, since on the one hand, processes at physical, MAC and network layers are used to generate a robust position and topology information; on the other hand, the generated position information is preciously useful in the optimization of processes at all the mentioned layers. Of particular importance is that we also involve the physical layer in the overall cross-layer optimization, an approach that is new compared to traditional approaches where more or less, generally only upper layers are considered (i.e., from layer 2 to 4). Besides, the position determination is fully integrated in the communication process. There is basically no crucial need of an external positioning infrastructure.

The essence of the research avenue lies in the fact that, from an information theoretical point of view, information available at different layers of the protocol stack contains per se a certain degree of redundancy that can be used for cross layer optimization. And we have proposed an architecture and a series of concepts that are specifically based on this, resulting in a synergy effect that leads to an overall improvement of the networking efficiency.

Our research plan will consider a series of key technologies at physical layer: OFDM and UWB. For the upper layer networking concepts we will consider WLAN, HyperLAN, and Bluetooth, besides 3G, 4G and hybrid networking scenarios, i.e., a combination of 3G with short-range hotspots (WLAN, Bluetooth, UWB).

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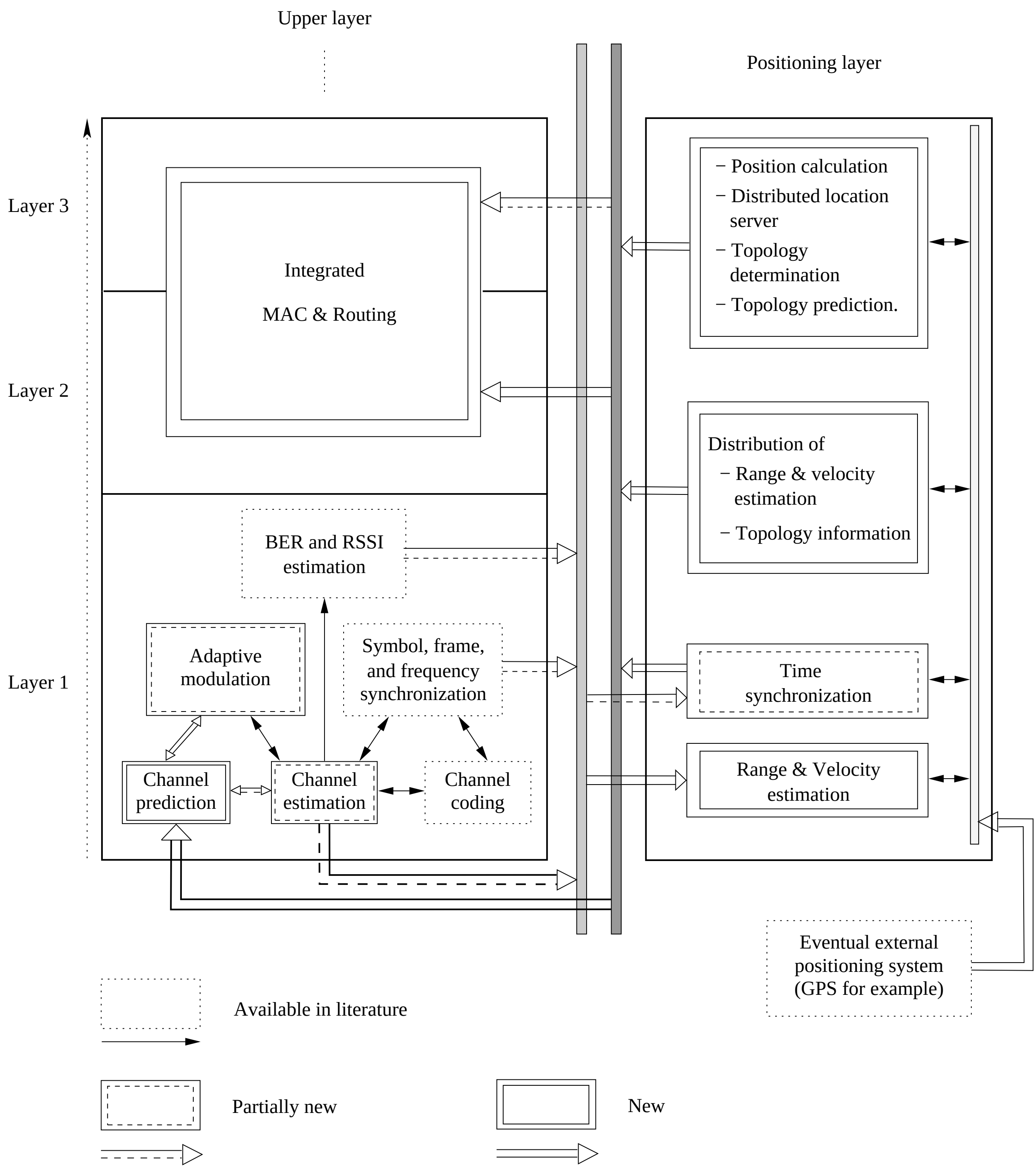

Fig. 1. Position determination scheme: on the one hand generation & calculation of the position, and on the other hand involvement of position information in processes at the layers 1 to 3 of the protocol stack

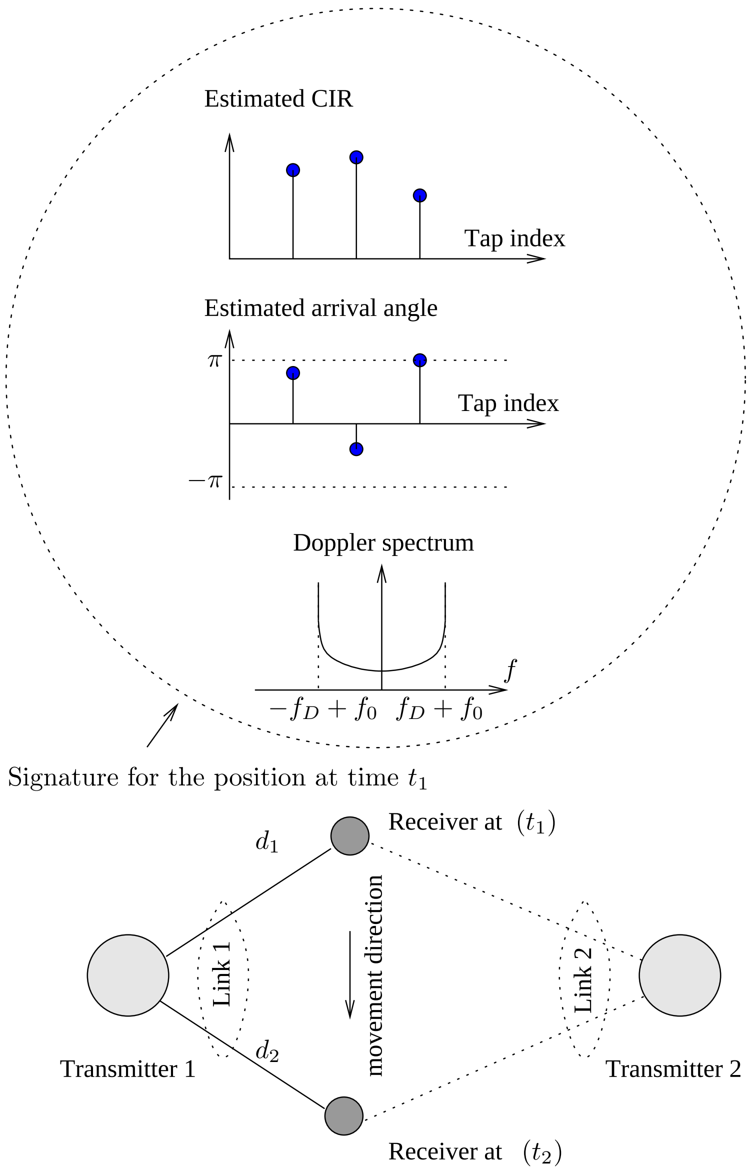

Fig. 2. Position determination based on the estimated channel.

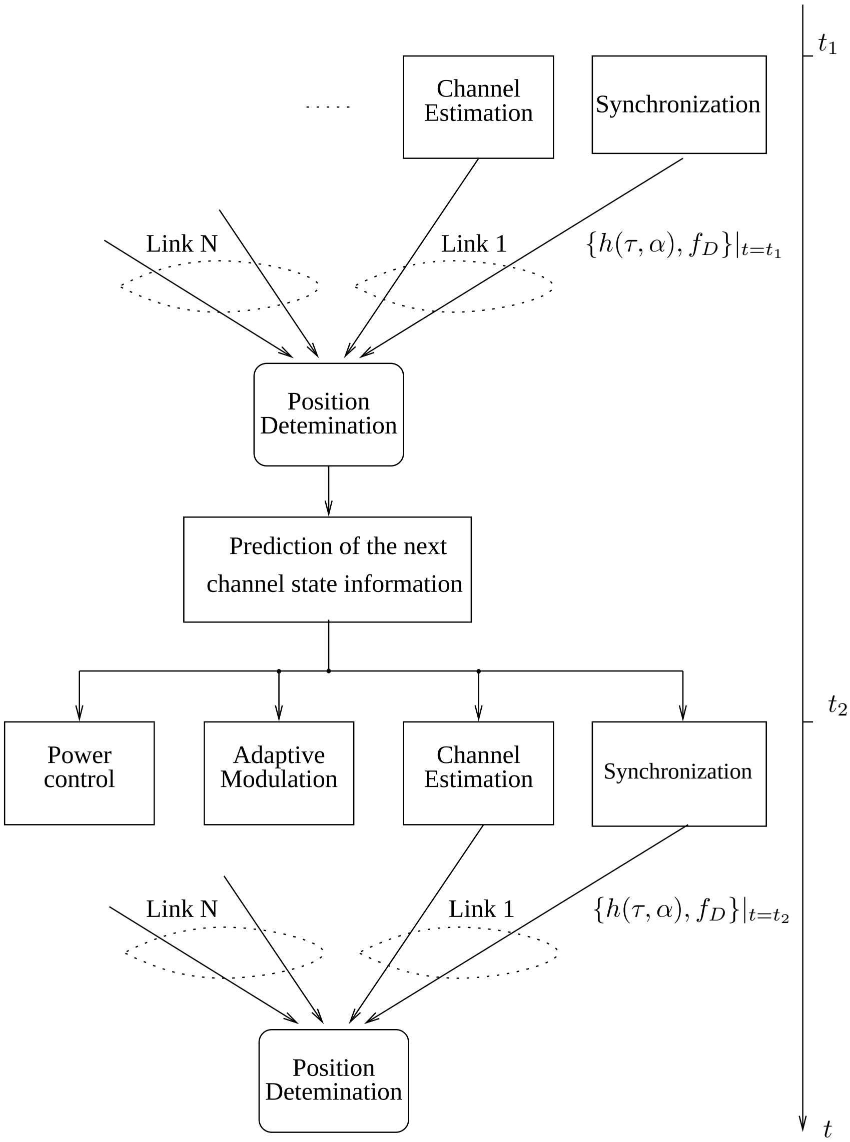

Fig. 3. Relation between channel estimation, synchronization and position determination.

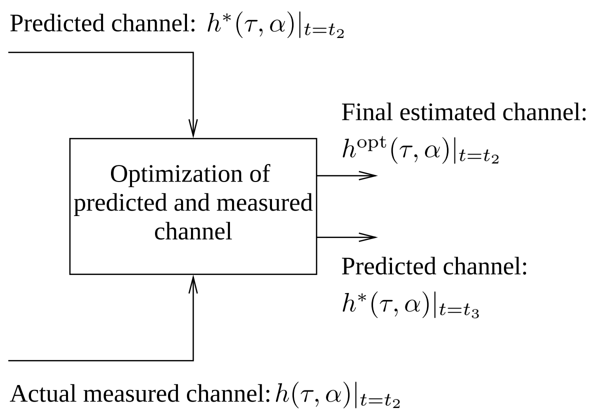

Fig. 4. Optimization of channel estimation using predicted and measured channel coefficients.